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Preface

This publication, the 14th and 15th parts of a group of publications dealing with the hydraulics of closed conduit spillways, reports tests on antivortex walls and low-stage inlets for a two-way drop inlet. The previous 13 parts were published as technical papers or Agricultural Research Service (ARS-NC Series) publications all under the major title "Hydraulics of Closed Conduit Spillways." The papers were published by the St. Anthony Falls Hydraulic Laboratory (SAFHL), University of Minnesota, Minneapolis. The earlier publications are:

Part I. Theory and Its Application, by F. W. Blaisdell. SAFHL Tech. Paper No. 12, Ser. B, 22 pp., illus., Jan. 1952 (rev. Feb. 1958). Gives theory, symbols, and bibliography.

Parts II through VII. Results of Tests on Several Forms of the Spillway, by F. W. Blaisdell. SAFHL Tech. Paper No. 18, Ser. B, 50 pp., illus., March 1958. Parts II through VI describe the hydraulic performance and present discharge coefficients for five forms of the closed conduit spillway; Part VII discusses vortices and their effect on the spillway capacity.

Part VIII. Miscellaneous Laboratory Tests; Part IX. Field Tests, by F. W. Blaisdell. SAFHL Tech. Paper No. 19, Ser. B, 54 pp., illus., March 1958. Reports tests on models of specific field structures and on field structures themselves.

Part X. The Hood Inlet, by F. W. Blaisdell and C. A. Donnelly. SAFHL Tech. Paper No. 20, Ser. B, 41 pp., illus., April 1958. Reports on the development of the hood inlet.

Part XI. Tests Using Air, by F. W. Blaisdell and G. G. Hebaus. SAFHL Tech. Paper No. 44, Ser. B, 53 pp., illus., Jan. 1966. Discusses the use of air for tests of closed conduit spillways.

Part XII: Two-Way Drop Inlet with a Flat Bottom, by C. A. Donnelly, G. G. Hebaus, and F. W. Blaisdell, U.S. Dept. Agr., Agr. Res. Serv., ARS-NC-14, 66 pp., illus., September 1974. Discusses tests on a covered rectangular drop inlet with a flat bottom where the water enters only over the two sides, and presents recommendations for the spillway design.

Part XIII: The Hood Drop Inlet, by K. Yalamanchili and F. W. Blaisdell, U.S. Dept. Agr., Agr. Res. Serv., ARS-NC-23, 78 pp., illus., August 1975. Describes the hood drop inlet and gives recommendations for its proportioning and hydraulic design.

Summary

Part XIV of this publication presents the results of experiments on antivortex devices for use with closed conduit spillway drop inlet entrances. The types of entrances investigated are hood drop inlets, rectangular drop inlets, square drop inlets, and circular drop inlets. The effects of drop inlet depth, approach channel depth, antivortex wall location, and antivortex wall dimensions on the ability of the device to inhibit harmful vortices is evaluated. Criteria are recommended for the design of antivortex devices. Where data are available, the laboratory findings are compared with field observations and the laboratory findings of other researchers.

Experiments on low-stage inlets for the two-way drop inlet are reported in Part XV. The effect of the location in the drop inlet and proportions of low-stage orifices on the performance are evaluated. Information is presented on the capacity of the orifice.

Contents

Hydraulics of Closed Conduit Spillways

Part XIV: Antivortex Walls for Drop Inlets

By Charles A. Donnelly and Fred W. Blaisdell[1]

Introduction

A device to control the formation of vortices at the entrance to closed conduit spillways is a necessity. Air entering the spillway through a vortex replaces the water, thus reducing the rate of flow of water discharging through the spillway. The reduction in discharge increases as the vortex strength increases. An antivortex device is needed to prevent a vortex from forming and impairing the spillway discharge capacity.

The greatest need for the antivortex device is at low submergences of the inlet when the spillway first flows completely full. This occurs for discharges just exceeding those where the weir at the drop inlet crest controls the head-discharge relationship.

The vortex and its effect on the spillway capacity are not steady. Sometimes there is no vortex even in the absence of an antivortex device. At other times there may be only surface circulation, or a vortex depression may develop without a deep core and without affecting the spillway capacity. At still other times a deep vortex core will extend into the inlet and admit considerable air to the conduit with the air replacing the water and thereby greatly reducing the flow of water through the spillway. Then the vortex may disappear, the airflow will stop, and the discharge will revert to the spillway full-flow capacity. Unless vortices are inhibited a reliable prediction of the flow cannot be made and a unique head-discharge relationship cannot be attained.[2]

Experiments were made on antivortex walls of various dimensions and forms located in several positions to determine which sizes and arrangements were most effective in controlling vortices. The antivortex walls were tested on four different types of drop inlets: the hood drop inlet, the rectangular drop inlet, the square drop inlet, and the circular drop inlet.[3] The tests were performed using the apparatus described in Part X[4] of this series. The 2.25-inch inside diameter barrel was on a 20 percent slope for all tests. Dimensions in this report are expressed in terms of the pipe diameter D.

The performance of the antivortex walls was rated either poor, fair to poor, fair to good, or good. A poor performance rating indicates that air was sucked in through strong vortices and caused variations in the spillway discharge and fluctuations in the headpool water level. A fair to poor rating indicates that the vortices were strong for a short period and caused some change in the discharge and in the headpool level. A fair to good rating means that small vortices formed and admitted a small amount of air, but they did not affect the head-discharge relationship. A good rating indicates that there was no fluctuation in either the discharge or the headpool level.

Antivortex walls for each drop inlet type will be discussed separately.

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[2]The important and adverse effect of vortices on the head-discharge relationship is shown in figure X-11. See reference to Part X in Preface.

[3]Tests on the flat plate antivotex device for the two-way drop inlet are given in Part XII. See reference in Preface.

[4]The Roman numerals in reference to equations, figures, parts, and tables refer to a particular Part of this series cited in the Preface.

Hood Drop Inlet Antivortex Walls[5]

Tests were made on a hood drop inlet 2D square by 2.04D deep to determine the minimum height of the splitter-type antivortex wall required to prevent vortices from reducing the spillway capacity.

The Model

The splitter-type antivortex wall used for the tests is rectangular when viewed from the side. It was placed on the longitudinal centerline of the drop inlet as shown in figure XIV-1. Its thickness was 0.028D, except for test S-6 when the thickness was 0.056D. As shown in figure XIV-1, the splitter wall may extend downward into the drop inlet to provide structural support for the wall. The length of the wall is equal to the outside dimension of the drop inlet, 2.22D for these tests. The height of the wall is the distance from the crest of the drop inlet to the top of the splitter wall. The model drop inlet was made of 1/4-inch-thick clear plastic, which gave the square-edge crest a thickness of 0.111D. The hood length was 0.75D.

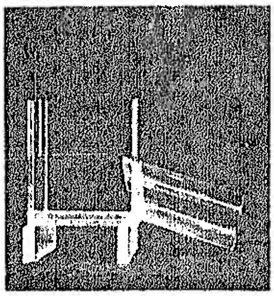


Figure XIV-1.—Model hood drop inlet with antivortex wall on longitudinal centerline.

Test Results

The variables tested and the results of the tests are listed in table XIV-1. The details which underlie the performance ratings are given for each test series in the following paragraphs.

TABLE XIV-1.—*Tests on the hood drop inlet*

Series	Height of wall above crest	Extension of wall below crest	Performance rating
S-1	0.00D	1.06D	Poor
S-2	.25D	1.06D	Poor
S-3	.50D	1.06D	Poor
S-4	.75D	1.06D	Fair to poor
S-5	1.00D	1.06D	Good
S-6	1.00D	.00D	Good

For series S-1 the antivortex wall did not extend above the drop inlet crest; it was entirely within the drop inlet. The test data are plotted as squares in figure XIV-2. For weir-controlled flow, which existed for relative heads H/D less than about 0.84, the data can be represented by

[5]The hydraulic performance of the hood drop inlet is presented in Part XIII.

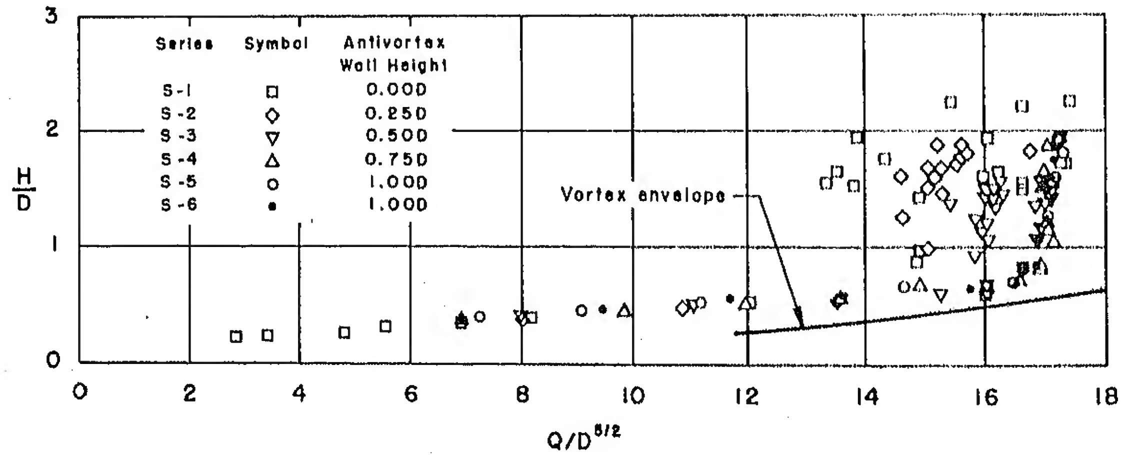


Figure XIV-2.—Head-discharge data for closed conduit spillway with hood drop inlet 2D square by 2.04D deep.

a smooth curve. At greater heads the flow control was the pipe, a strong vortex was present, and the spillway discharge fluctuated widely because of fluctuations in the vortex strength and variations in the amount of air admitted to the spillway through the vortex core.

All square data in figure XIV-2 for $H/D >$ 0.84 were obtained with a constant headpool inflow rate $Q/D^{5/2}$ of 16.6. As the vortex strength fluctuated, the headpool level varied over the range $0.84 \leqq H/D \leqq 2.26$, and the spillway outflow ranged from $13.4 \leqq Q/D^{5/2} \leqq 17.4$. From the scatter of the data plotted in figure XIV-2, obviously the head-discharge relationship is unpredictable when the flow control is the pipe. Therefore, the performance of the antivortex wall which does not extend above the drop inlet crest is rated poor.

Strong vortices formed and entrained a considerable amount of air when the splitter wall was 0.25D high (series S-2) or 0.50D high (series S-3). These vortices were of long duration. The data plotted in figure XIV-2 show the fluctuating discharge caused by the vortices. For the 0.25D-high wall $14.6 \leqq Q/D^{5/2} \leqq 17.1$ and for the 0.50D-high wall $15.4 \leqq Q/D^{5/2} \leqq 17.1$. These data make clear that increasing the antivortex wall height decreases the range of fluctuation of $Q/D^{5/2}$. However, because the vortices were strong and they caused considerable fluctuation in the flow through the spillway, the performance for these wall heights is rated poor.

When the 0.75D-high wall (series S-4) was tested, vortices appeared intermittently, but strong vortices lasted for only a short time and little headpool fluctuation occurred. The data show that the discharge fluctuation was $17.0 \leqq Q/D^{5/2} \leqq 17.1$. The small fluctuations in headpool level and in the discharge indicate that this wall height is close to the minimum required to completely control the effect of vortices. For this reason the performance for the wall 0.75D high is rated fair to poor.

Two series of tests were made with a splitter wall 1D high. For series S-5 the splitter wall protruded into the drop inlet. For series S-6 the splitter wall was placed on top of the drop inlet crest, and it did not protrude into the drop inlet. There was no difference in the performance of these two walls. For both walls the vortices that formed were either on the water surface or they admitted only a small amount of air for a short time. Figure XIV-2 shows that these small vortices did not affect the head-discharge relationship. The performance was rated good. The conclusion from the results of the series S-5 and S-6 tests is that the extension of the antivortex wall into the drop inlet does not contribute significantly to the control of vortices.

During series S-5 and S-6, however, there was a current on the downstream side of the drop inlet which could cause erosion of the dam fill. Data reported in Part V of this series of publications indicate that extending the splitter wall into the dam fill will eliminate this current.

Recommendations

The authors recommend that the splitter-type antivortex wall for a hood drop inlet 2D square have a minimum height of 1.0D. The splitter wall may extend into the drop inlet if desired. Extending the splitter wall into the dam fill will eliminate the circulation downstream of the drop inlet and prevent erosion of the dam face.

Rectangular Drop Inlet Antivortex Walls

Experiments were performed on the rectangular drop inlet shown in figure XIV-3 to determine the height, location, and orientation of antivortex walls required to control harmful vortices.

The Models

A model of the rectangular drop inlet with the transverse antivortex wall located one-third the distance of the drop inlet length from the downstream end is shown in figure XIV-4. The barrel entrance edge was square, and the barrel slope was 20 percent for all tests.

The dimensions of the drop inlets and antivortex walls tested are given in table XIV-2 and figure XIV-3. As shown in figure XIV-3 the inside width of the rectangular drop inlet was always equal to the inside diameter of the barrel. The sidewalls and endwalls were 0.111D thick.

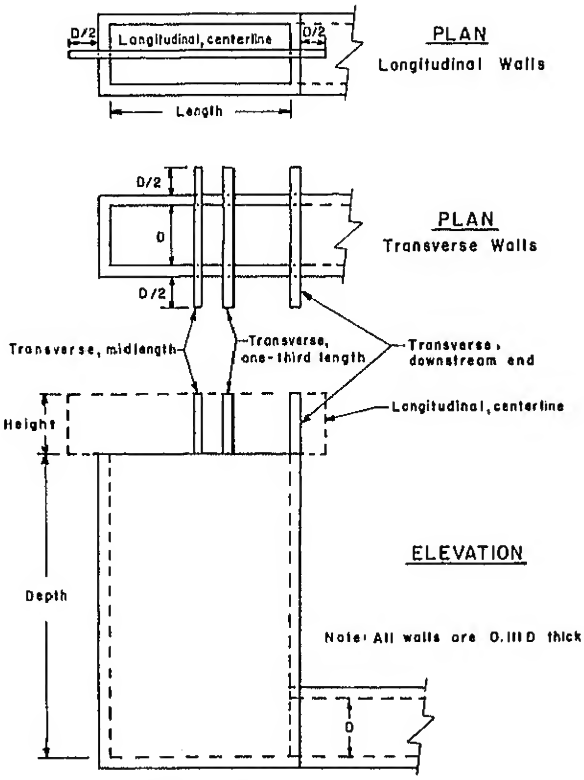


Figure XIV-3.—Test locations of antivortex walls on rectangular drop inlet.

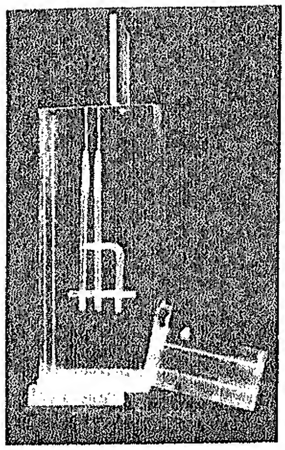


Figure XIV-4.—Model of a rectangular drop inlet with transverse antivortex wall at one-third the drop inlet length. Piezometer tubes are for measuring pressures on the crest and at midheight.

Test Results

The results of the tests are summarized in table XIV-2. Following are comments on the drop inlet depth, on the lack of effect of the approach channel depth, and on the performance of the various antivortex walls.

TABLE XIV-2.—*Tests on the rectangular drop inlet*

Series	Drop inlet		Antivortex wall			
	Depth	Length	Orientation	Location	Height	Performance
S-7	4D	3.0D	Transverse	Downstream endwall	1.0D	Poor
S-8	4D	3.0D	Transverse	Midlength	1.0D	Poor
S-9	4D	3.0D	Longitudinal	Centerline	1.0D	Good
S-10 ...	4D	3.0D	Transverse	One-third length	1.0D	Good
S-11[1] ..	4D	3.0D	None	....	....	Poor
S-12[1] ..	4D	3.0D	Transverse	Downstream endwall	1.0D	Poor
S-13[1] ..	4D	3.0D	Transverse	One-third length	1.0D	Fair to good
S-14[1] ..	4D	3.0D	Transverse	One-third length	2.0D	Good
S-15[1] ..	4D	3.0D	Transverse	One-third length	1.5D	Good
S-16 ...	4D	2.0D	None	....	....	Poor
S-17 ...	4D	2.0D	Transverse	Midlength	1.0D	Poor
S-18 ...	4D	2.0D	Transverse	One-third length	1.0D	Good
S-19 ...	4D	2.0D	Transverse	Downstream endwall	1.0D	Poor
S-20 ...	5D	2.0D	Longitudinal	Centerline	1.0D	Good
S-21 ...	5D	2.0D	Transverse	One-third length	1.0D	Good
S-22 ...	5D	5.0D	Transverse	Downstream endwall	1.5D	Fair to good
S-23 ...	5D	5.0D	Transverse	Midlength	1.5D	Fair to good
S-24 ...	5D	5.0D	Transverse	One-third length	1.5D	Good
S-25 ...	5D	5.0D	Longitudinal	Centerline	1.0D	Good
S-26 ...	5D	1.5D	Transverse	Downstream endwall	1.5D	Poor
S-27 ...	5D	1.5D	Transverse	Midlength	1.5D	Good
S-28 ...	5D	1.5D	Transverse	One-third length	1.5D	Good
S-29 ...	5D	1.5D	Longitudinal	Centerline	1.0D	Good

[1]Floor in approach channel at crest elevation.

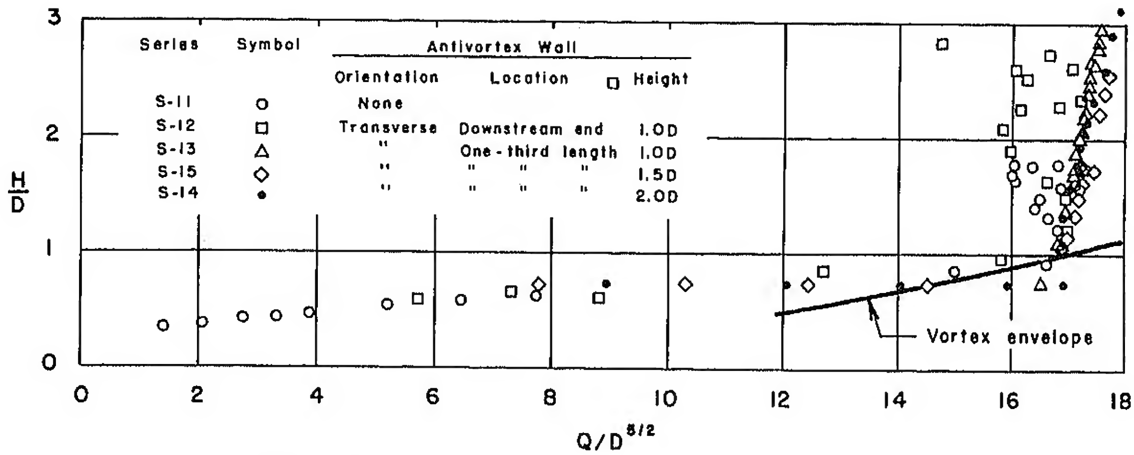


Figure XIV–5.—Head-discharge data for closed conduit spillway with rectangular drop inlet 3D long, 1D wide, 4D deep, and approach channel at crest elevation.

Drop Inlet Depth

When the drop inlet was 4D deep, orifice flow occurred at the barrel entrance during series S-12 and S-18. This caused the headpool level for series S-18 to first peak at a head of 0.78D then to fluctuate between 0.46D and 0.57D as the barrel primed and lost its prime. For series S-12 there was a single orifice flow peak at a head of 2.65D, the head at which the barrel primed. When the drop inlet was 5D deep, the undesirable orifice flow occurred only for series S-21 but did not affect the headpool level.

These findings verified the results of experiments on the square drop inlet which showed that, to insure priming, the drop inlet must be at least 5D deep when the barrel entrance is square-edged.[6]

[6]See p. 29, Part V.

Approach Channel Depth

Two conditions of approach to the inlet were tested for the 3D-long drop inlet. The condition used for series S-11 through S-15 had a false floor at crest elevation and a 1-on-2 dike slope beginning at the downstream end of the crest. For the second condition, used for most of the experiments, the approach floor was below the bottom of the drop inlet so the approach channel was deep.

Comparing figure XIV-5 with figure XIV-6 shows that the level approach increased the head

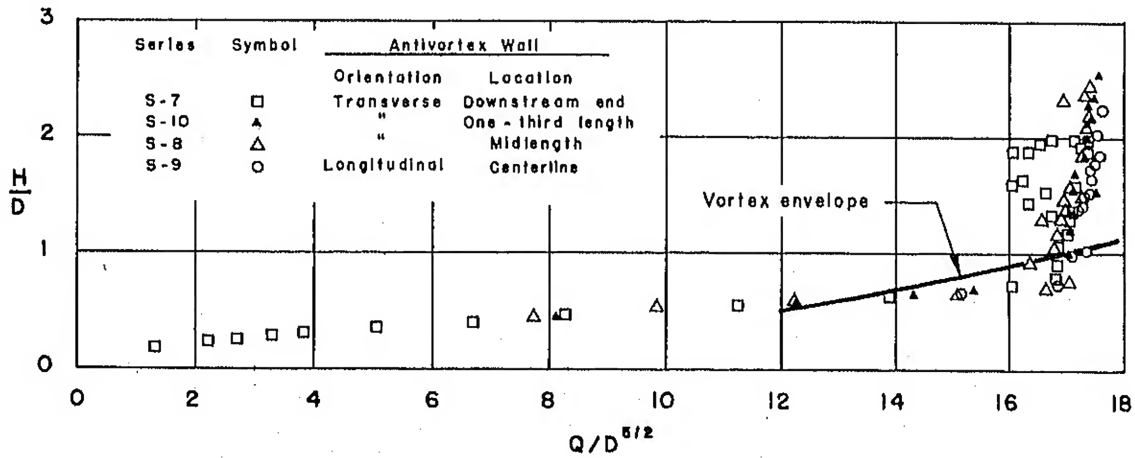


Figure XIV–6.—Head-discharge data for closed conduit spillway with rectangular drop inlet 3D long, 1D wide, 4D deep, 1D antivortex wall height, and deep approach channel.

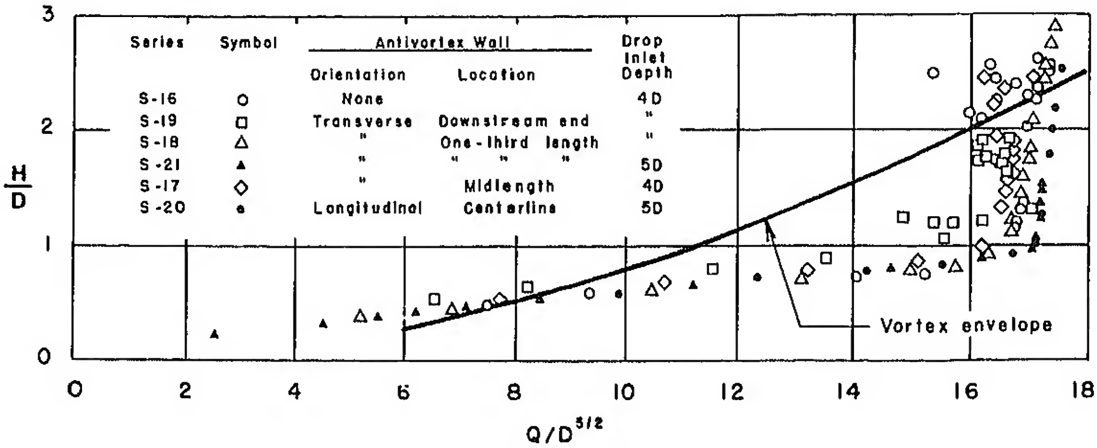


Figure XIV-7.—Head-discharge data for closed conduit spillway with rectangular drop inlet 2D long, 1D wide, 1D antivortex wall height, and deep approach channel.

during weir flow but that it had little effect on the head-discharge relationship for full-pipe flow.

The lack of effect of approach channel depth on the head-discharge relationship for full-pipe flow can best be seen by comparing the data obtained for otherwise similar conditions presented in figures XIV-5 (crest elevation approach) and XIV-6 (deep approach).

Comparisons can be made only for two transverse antivortex wall orientations. For series S-12 (crest elevation aproach) and series S-7 (deep approach) the antivortex wall location is at the downstream end of the drop inlet. The spread of the data points—the squares—at relative heads $H/D > 0.75$ indicates the presence of strong vortices for both approach channel depths. The performance rating is poor for both series.

In the second comparison, the antivortex wall is at one-third the drop inlet length for series S-13 (crest elevation approach) and series S-10 (deep approach). The data points—the open triangles for series S-13 and the solid triangles for series S-10—define good head-discharge relationships. Again the two approach channel depths produce similar results even though the performance ratings are good for series S-10 and fair to good for series S-13.

The results of these tests indicate that the approach channel depth does not influence either the presence or the absence of vortices. To ease model installation, tests subsequent to series S-15 were made with the deep approach.

Absence of Antivortex Wall

Tests were run without an antivortex wall for drop inlet lengths of 3D (series S-11) and 2D (series S-16). The data for series S-11 are plotted in figure XIV-5 and for series S-16 in figure XIV-7. The scatter of the plotted data—the circles in figures XIV-5 and XIV-7—shows that an unpredictable head-discharge relationship existed when the barrel was full. This was due to the strong vortex action that admitted a considerable amount of air. The strong vortices continued for long periods. The performance ratings for these series are poor.

These tests show that some type of antivortex device is necessary to insure a predictable head-discharge relationship.

Antivortex Wall Location

The transverse antivortex wall was located at three positions: over the downstream endwall, at the drop inlet midlength, and at one-third the drop inlet length upstream from the downstream endwall. The longitudinal antivortex wall was located only on the drop inlet longitudinal centerline, and information on its performance is available only for this one position.

The transverse wall placed over the downstream endwall for the 5D-long drop inlet (series S-22, squares in figure XIV-8) was given a fair to good performance rating. The vortices that formed were small, and so little air was entrained that the head-discharge curve was not affected. However, the performance of the

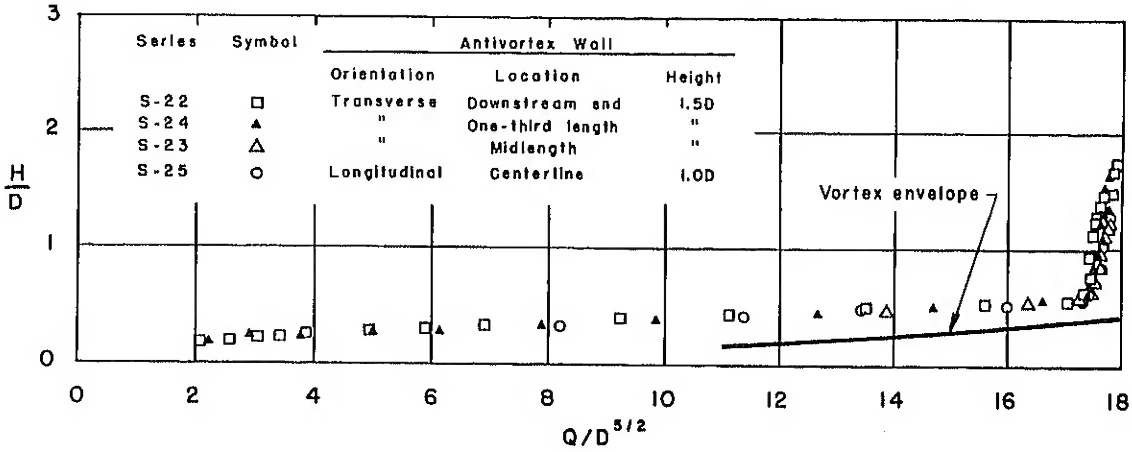


Figure XIV–8.—Head-discharge data for closed conduit spillway with rectangular drop inlet 5D long, 1D wide, 5D deep, and deep approach channel.

transverse wall placed over the downstream endwall was rated poor for drop inlet lengths of 1.5D (series S-26, squares in figure XIV-9), 2D (series S-19, squares in figure XIV-7), and 3D (series S-7, squares in figure XIV-6). For these series, strong vortices formed and sucked in a considerable amount of air. This caused an unpredictable head-discharge relationship when the transverse antivortex wall was located over the downstream endwall.

Obviously, from the data presented in the figures and the ratings given in table XIV-2, an antivortex wall located over the downstream endwall of the drop inlet does not satisfactorily control vortices. Also, the resulting head-discharge relationship is unpredictable.

When the transverse wall was placed at the midlength of the 5D- and 1.5D-long drop inlets (series S-23, open triangles in figure XIV-8; and series S-27, open triangles in figure XIV-9), small vortices formed and admitted a small amount of air, but the vortices did not affect the head-discharge relationship. The head-discharge data for these series can be represented by a single line. However, strong vortices formed downstream from the antivortex wall for the 2D and 3D drop inlet lengths.

The data for these latter series do not define a unique head-discharge relationship (series S-8, triangles in figure XIV-6; and series S-17, squares rotated 45° in figure XIV-7). In spite of the ratings of good for series S-27 (1.5D drop

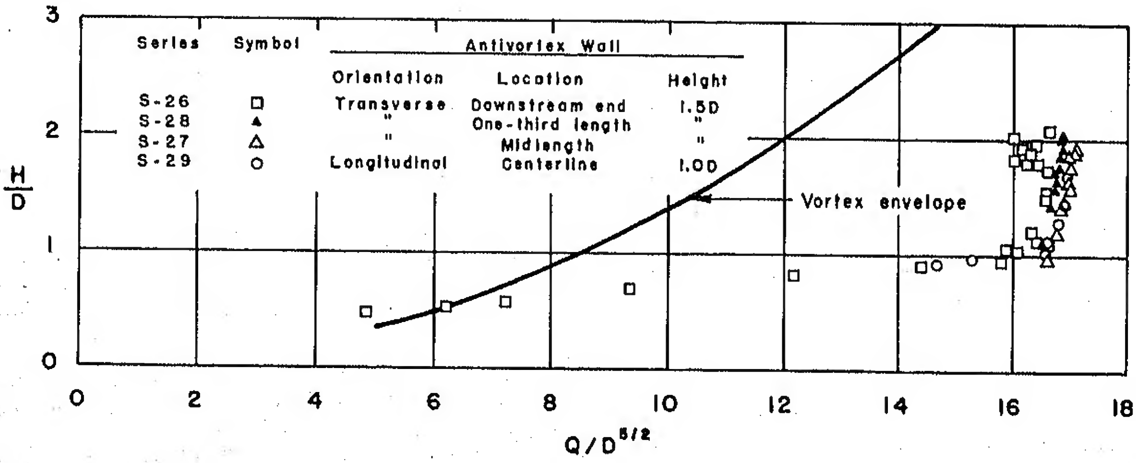


Figure XIV–9.—Head-discharge data for closed conduit spillway with rectangular drop inlet 1.5D long, 1D wide, 5D deep, and deep approach channel.

inlet length) and fair to good for series S-23 (5D drop inlet length), the poor ratings given series S-17 (2D drop inlet length) and series S-8 (3D drop inlet length) indicate that a transverse antivortex wall located at the midlength of the drop inlet does not satisfactorily control the effects of vortices.

When the antivortex wall was removed, the vortex core was located at a point about one-third the drop inlet length from the downstream end. This distance was the most effective location for the transverse antivortex wall. The small vortices that formed entrained only small amounts of air when the transverse wall was placed at one-third of the drop inlet length from the downstream end. Several vortices looked strong, and the air being sucked in was audible; however, the vortices did not admit enough air to affect the head-discharge relationship.

Results of the tests on the antivortex wall located at the one-third point are shown in figure XIV-5 for series S-13, S-14 and S-15; figure XIV-6 for series S-10; figure XIV-7 for series S-18 and S-21; figure XIV-8 for series S-24; and figure XIV-9 for series S-28. Except for series S-13, all the performance ratings were good.

The test results show that locating the transverse antivortex wall one-third the drop inlet length upstream from the downstream endwall most effectively controls the adverse effects of vortices. The head-discharge relationship is reliably predictable with the transverse antivortex wall in this position.

Notwithstanding the good performance of the transverse antivortex wall located at the one-third length, the antivortex wall located on the longitudinal centerline gave the best results. The vortices that formed were on the surface, and they had no effect on the head-discharge relationship. Little circulation occurred around the downstream end of the drop inlet. Compare series S-9, figure XIV-6; series S-20, figure XIV-7; series S-25, figure XIV-8; and series S-29, figure XIV-9. Performance ratings for each of these series are good.

Antivortex Wall Heights

To reduce the noise and the visibly strong vortices, the transverse antivortex wall was raised from 1D (series S-13) to 1.5D (series S-15) and to 2D (series S-14). The data are plotted in figure XIV-5. Performance rating for series S-13 is fair to good, and for series S-15 and S-14 is good. Only surface vortices were present until the antivortex wall became submerged. After the wall was submerged, the vortices that formed admitted small amounts of air for short periods of time, but the head-discharge relationship was not affected. The results of these tests show that a transverse wall 2D high gives the best results, a wall 1.5D high is satisfactory, and a wall 1D high can be used but is less desirable.

For the longitudinal antivortex wall location, a wall 1D high satisfactorily controlled vortices so greater heights were not tested.

Field Comparison

Field observations were made in April 1967 of the performance of the rectangular drop inlet spillway at Upper Clear Boggy Creek Site No. 8 in Oklahoma. These field observations generally confirm the results of the laboratory tests reported here and of model tests conducted at the Stillwater, Okla., hydraulic laboratory of the Agricultural Research Service.[7]

The Upper Clear Boggy Creek drop inlet is 3.3D long, 1D wide and 2.67D deep. It has three transverse antivortex walls. These walls are located over the upstream and downstream ends and at the midlength of the drop inlet. The walls are 1.33D high and extend 1.75D beyond the outside of the drop inlet.

In an October 17, 1967, report from Horace M. Haws, Jr., head, Oklahoma Design Section, Soil Conservation Service (SCS), to William T. Burtschi, state conservation engineer, SCS, Stillwater, Okla., is the statement

> . . . Mr. Foreman [the landowner] stated that as the pool emptied from an elevation 8" above the inlet splitter wall [$H/D = 1.56$] to the elevation of the splitter [$H/D = 1.33$] that a reoccurring loud "clap" was audible at his home approximately one-half mile from the structure. This was accompanied by a sucking noise and slugging and surging of the outflow.

[7] Gwinn, W. R. and Hebaus, G. G. Hydraulic studies of noise and vibration in a two-way, open-top drop inlet spillway. U.S. Dept. Agr., Agr. Res. Serv., of the then Soil and Water Conserv. Res. Div., ARS 41-181, 16 pp., July 1972.

Considerable vibration of the embankment was reported during this period of slug flow. . . . Mr. Foreman reported that a single vortex located downstream from the splitter wall was evident during this period of slug or surging flow.

The Upper Clear Boggy Creek drop inlet has approximately the same proportions as the 3D-long, 1D-wide, and 4D-deep inlet used for series S-7 and S-8. For series S-7 the transverse antivortex wall was located over the downstream endwall whereas for series S-8 the wall was at the drop inlet midlength. The performance ratings for both series are poor. Strong vortices occurred for series S-7 and small vortices formed for series S-8. Only when the transverse antivortex wall was located at one-third the length of the drop inlet (series S-10) was the performance rated good.

Apparently the observed performance of the Upper Clear Boggy Creek spillway by Foreman is like that observed in the laboratory during tests on closely similar spillways.

The Stillwater test results also agree in general with Foreman's observations and with the findings reported above. Gwinn and Hebaus report:[8]

. . . careful attention was given to the flow behavior in the model. Of particular interest was the range in which the loud clap occurred in the prototype (H/D range from [1.33 to 1.56]). No such noise occurred during the model pipe control tests. However, the intensity of circulation over the downstream half of the drop inlet increased in this flow range. During each test, except for the one with the largest discharge, a small dimple formed and dissipated over the downstream half of the drop inlet. Whenever the top grating was removed from the model, a vortex with a long, slender air core formed in this area.[9] However, very little, if any, air was transported through the pipe.

. . . circulation in the form of a dimple-type vortex was noted for flows with headpool levels above the splitter wall, but neither noise nor vibration were noted in this range. From these observations, we concluded that if a vortex is observed in the model, one is likely to occur in the prototype, and that the vortex may be more violent in the prototype than in the model.

Although strong vortices were absent and air entry through the vortex core was small even without the top grating, the Stillwater tests confirm the findings reported herein: Transverse antivortex walls located over the downstream endwall and at the drop inlet midlength do not satisfactorily control the adverse effects of vortices.

The Upper Clear Boggy Creek spillway has passed flood flows several times since Foreman's April 1967 observations. No noise or vibration has been noted by the landowner since 1967. Regarding a flow event in October 1970, the 1970 Annual Report of the Stillwater laboratory states:

The laboratory staff were unable to reach the site when the headpool dropped through [the stage at which noise and vibration had occurred previously]. However, the landowner did not notice any noise as the structure flowed through the stage of interest. Neither could the staff detect any noise or vibration on the days they were at the site.

Apparently the noise and vibration reported were fortuitously related to some unknown factor.

Recommendations

For the rectangular open-top drop inlet the authors recommend a longitudinal antivortex wall 1D high extending D/2 beyond the drop inlet endwalls.

An alternate recommendation is a transverse antivortex wall located at one-third the drop inlet length upstream from the downstream endwall. This wall should extend D/2 beyond the outside of the drop inlet sidewalls. Its height should be at last 1.5D and preferably 2D or extend to the maximum water surface elevation, whichever is less.

Not recommended are transverse antivortex walls located over the downstream endwall and at the midlength of the drop inlet.

[8]See pages 6-7 of reference in footnote 7, p. 8.

[9]Both Gwinn (Gwinn, W. R. Tests of steel deck grating for vortex supression on closed conduit spillways. Unpublished data of the U.S. Agricultural Research Service, Stillwater (Okla.) Outdoor Hydraulic Laboratory) and Humphreys and Sigurdsson (Humphreys, H. W. and Sigurdsson, G. Effect of metal grating deck on drop-inlet spillway performance. Ill. Dept. Registr. and Ed., State Water Survey Div. Cir. 75, 8 pp., 1959) show that the grating reduces the vortex strength but does not completely control the effects of vortices. No grating was used during the tests reported in this paper.

Square Drop Inlet Antivortex Walls

Experiments were performed to determine the size and position of an antivortex wall for the square drop inlet. Although earlier tests had defined the hydraulics of the square drop inlet[10] and had shown that an antivortex wall was necessary[11] the effect of various antivortex wall orientations, locations, and dimensions had never been evaluated. A limited evaluation of antivortex walls for square drop inlets follows.

The Models

The drop inlets were 1.25D square in plan and were 4D deep, except a 5D-deep drop inlet was used for series 606. The square-edged crest of the drop inlet was 0.111D thick. The barrel was 2.25 inches in diameter, its entrance edge was square, and its slope was 20 percent.

Two different conditions of approach to the drop inlet were used. The approach floor was below the bottom of the drop inlet so the approach channel was deep for series 606 through 615. A false floor at crest elevation and a 1-on-3 dike slope beginning at the downstream end of the crest was used for series 616 through 621. This latter condition is shown in figure XIV-10.

The antivortex wall types tested and their dimensions are given in table XIV-3. The longi-

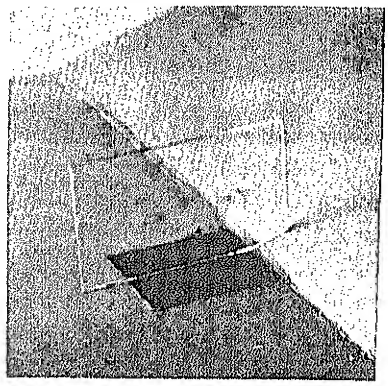


Figure XIV-10.—Square drop inlet with approach at crest elevation, antivortex wall 1.5D high and 0.5D extension placed on longitudinal centerline.

[10]See Parts IV and V.

[11]See "Circulation Around Anti-Vortex Walls," pp. 33-35, Part V.

TABLE XIV-3.—*Tests on the square drop inlet*

Series	Antivortex wall: Orientation	Location	Height	Extension[1]	Performance
606[2]	Longitudinal	Centerline	1.5D	1.0 D	Good
606A	Longitudinal	Centerline	1.5D	1.0 D	Good
607	Longitudinal	Centerline	1.5D	1.0 D	Good[3]
608	Transverse	Downstream endwall	1.5D	1.0 D	Poor[3]
609	Longitudinal	Centerline	1.5D	0.5 D	Good[3]
610	Transverse	Midlength	1.5D	0.5 D	Good
611	Longitudinal	Centerline	1.0D	0.5 D	Poor
612[4]	Longitudinal	Centerline	1.5D	0.5 D	Good
613	Longitudinal	Centerline	1.5D	0.25D	Good
614	Transverse	Midlength	1.5D	0.25D	Fair to good[3]
615	Longitudinal	Centerline	1.5D	0.0 D	Poor
616[5]	Longitudinal	Centerline	1.5D	1.0 D	Good[6]
617[5]	Longitudinal	Centerline	1.5D	0.5 D	Good[6]
618[5]	Transverse	Downstream endwall	1.5D	1.0 D	Poor
619[5]	Longitudinal	Centerline	1.5D	0.25D	Fair to good
620[5]	Longitudinal	Centerline	1.5D	0.5 D	Good
621[5]	Transverse	Midlength	1.5D	0.5 D	Fair to good

[1]Beyond outside wall of drop inlet.
[2]Drop inlet 5D deep. Depths for other series are 4D.
[3]Tests cover full-pipe range of flows only.
[4]Antivortex wall 0.333D thick. Other walls are 0.083D thick.
[5]Floor in approach channel at crest elevation.
[6]Tests cover weir, slug, and mixture range of flows only.

tudinal antivortex walls were placed on the longitudinal centerline of the drop inlet. Transverse antivortex walls were located either at the drop inlet midlength or over the downstream endwall. When the antivortex wall was placed over the downstream endwall, one-fourth of the drop inlet crest length was blocked off. The crest length reduction when the wall was at the midlength or centerline was two times the wall thickness. The antivortex walls crossed the drop inlet, and the walls extended beyond the outside of the drop inlet from 0.0D to 1.0D.

Test Results

The results of the antivortex wall tests are summarized in table XIV-3 under the heading Performance. The tests and results are discussed in the following paragraphs.

Drop Inlet Depth

Several tests were performed to evaluate the effect of drop inlet depth on the spillway performance.

The minimum recommended drop inlet depth is 5D. (See page 35 of Part V.) The drop inlets used for the present tests are, with one exception, 4D deep—1D less than minimum previously recommended. A reason for using this lower drop inlet depth for these tests was to check the previous recommendation.

Notes taken during series 610, 611, 612, 613, 617, 619 and 621 state that the barrel primed, indicating that the spillway performance was satisfactory for these 4D-deep drop inlets. The priming characteristic for the remaining series was not recorded.

The performance of the 4D-deep drop inlets was barely adequate. This conclusion is the result of a study of the headpool water level recorder charts. The chart trace of the headpool water level shows a small hump for series 606A, 612, 613, 617, 618, 620, and 621 indicating that the priming was delayed. The relative discharges between which these humps occurred had an average range of $6.5 < Q/D^{5/2} < 7.9$ and a maximum range of $6.3 < Q/D^{5/2} < 8.6$ when the data for series 613, which did not follow the pattern of the other data, were eliminated. The actual value of $Q/D^{5/2}$ at which priming took place was not determined. However, if the average of the average range cited can be taken as the priming discharge, it appears that the priming value of $Q/D^{5/2}$ is about 7.2. That the onset of slug flow for the two-way drop inlet 1.5D long is $Q/D^{5/2} >$ 6.7 to 7.4,[12] which is within the range obtained for the 1.25D-square drop inlet, may be a coincidence.

There was no hump in the headpool water level recorder trace for series 606 when the drop inlet depth was 5D. The hump was absent also for for series 611, 615, 616 and 619. No data were obtained in the priming range of discharges during series 607, 608, 609, 610 and 614.

The data obtained during the tests on the 1.25D-square drop inlet indicate that the priming potential of the 4D-high drop inlet is borderline: The previously recommended minimum depth of 5D should be adhered to when the barrel entrance edge is square.

Approach Channel Depth

The effect of approach channel depth on the performance is evaluated by comparing the performance ratings and notes taken during the tests for those series that were otherwise similar.

For the longitudinal antivortex walls 1.5D high and extending 1.0D and 0.5D beyond the outside edge of the drop inlet, the performance ratings are good for both approach channel depths. The data sheets contain comparable notes indicating that only after submergence of the antivortex wall did small amounts of air enter through vortices. The air did not affect the head-discharge relationship. When the extension was reduced to 0.25D, similar good results were obtained when the approach was deep (series 613). But for the crest elevation approach depth (series 619), vortices at the higher heads admitted air and the performance was rated fair to good. However, the headpool recorder trace shows only slight variations in the head.

For the transverse antivortex wall at the downstream end of the drop inlet, the performance is rated poor for both approach channel depths. The test notes state that the vortices were strong.

For the transverse antivortex wall located at

[12]See Part XII, "Test Results; Spillway Performance; Priming; Minimum Antivortex Plate Height."

the drop inlet midlength, the performance with the deep approach channel is rated good (series 610); and when the approach channel is at crest elevation, the rating is fair to good (series 621). The test notes indicate that during series 621 air was admitted to the spillway. However, the headpool water level recorder charts do not show significantly greater irregularity for series 621 than for series 610. Therefore, the test observations and the ratings assigned during the test were relied on to determine the performance rating.

The results of these tests indicate that when the approach channel is at the crest elevation there is a slight, possibly unimportant, reduction in the performance over that observed when the channel approaching the drop inlet is deep.

Antivortex Wall Location

Only one location was used for the antivortex wall located on the longitudinal centerline of the drop inlet. This location provided good vortex control when the criteria regarding dimensions were met. The data from series 620 plotted as circles in figure XIV-11 show a typical unique head-discharge relationship that was obtained using the longitudinal splitter wall.

The transverse antivortex wall was located either at the drop inlet midlength or over the downstream endwall. Performance ratings for the downstream endwall position are poor. (See series 608 and 618.) For the downstream endwall position of the antivortex wall the headpool water level recorder charts show erratic variations in the headpool level. These variations verify the test notes stating that the vortices were strong. Additional indication that this antivortex wall location is poor can be derived from the data for series 618 plotted as squares in figure XIV-11. At the higher discharges where the pipe was full, the data do not define a unique head-discharge relationship. This is because the varying strength of the vortices caused variations in the rate of flow through the spillway.

The findings reported in Part V also support the conclusion that an antivortex wall located over the downstream endwall does not adequately control vortices and circulation. The following quotation is from Part V:

> Early in the test program, considerable difficulty was experienced in obtaining similar head-discharge curves for supposedly similar spillways that differed only in size. This was finally traced to the effect of different amounts of circulation around the headwall. Excellent agreement was obtained after all circulation around the headwall was prevented by means of a dike between the headwall and the downstream end of the test channel.

When the transverse antivortex wall was located at the drop inlet midlength, the performance ratings are good for series 610 (deep approach channel) and fair to good for series 621 (crest elevation approach channel). The data for series 621 are plotted as triangles in figure XIV-11. They show a slight nonuniqueness in the full-pipe range of discharges. Additionally the water level recorder chart shows a

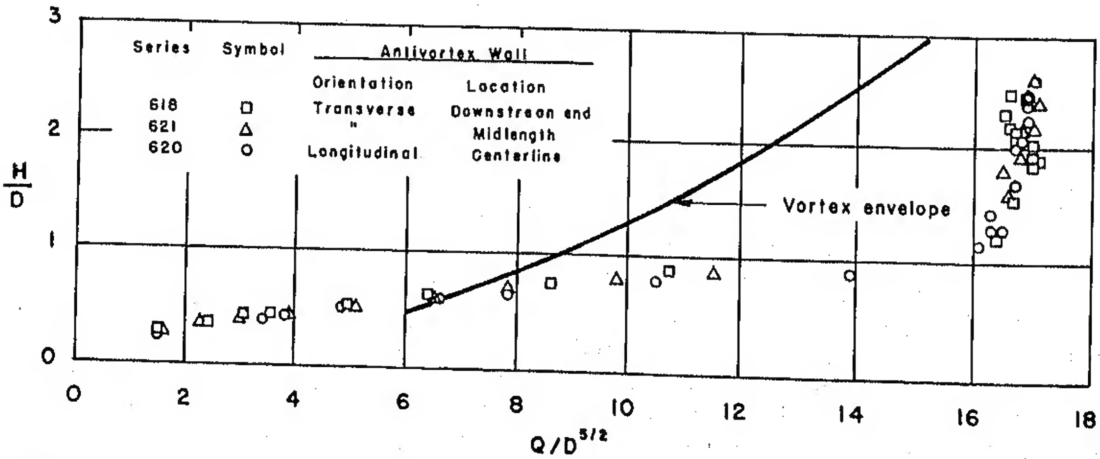
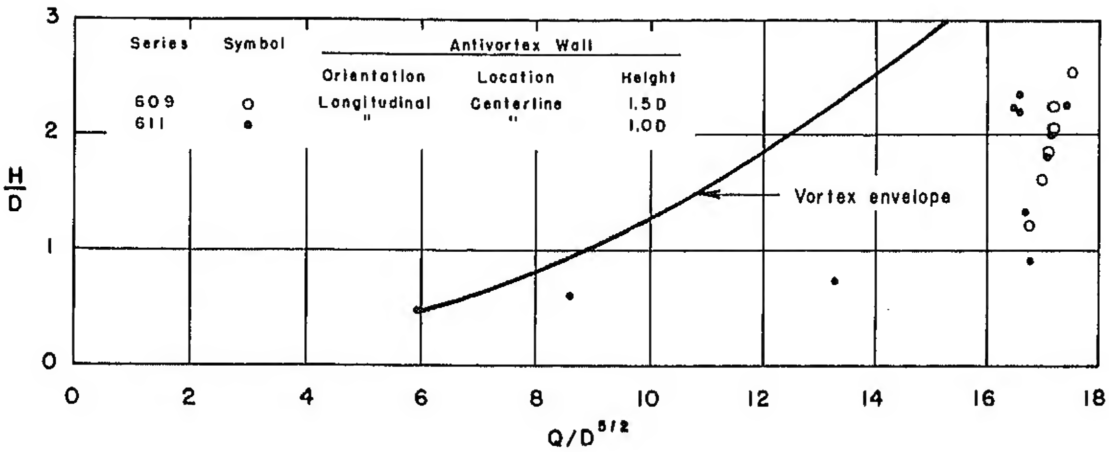


Figure XIV-11.—Head-discharge data for closed conduit spillway with 1.25D-square drop inlet showing effect of the antivortex wall location.



ɾure XIV-12.—Head-discharge data for closed conduit spillway with 1.25D-square drop inlet showing effect of antivortex wall height.

:le irregularity in the record. Figure XIV-11 1 the chart thus verify the test note that air :ered the spillway for short periods of time 1 the assigned fair to good performance rat- :.

Γhe results of these tests indicate that the ıt location of the antivortex wall is on the gitudinal centerline of the drop inlet. A trans- :se antivortex wall located at the drop inlet 1length is satisfactory when the approach to ɛ drop inlet is deep; but when the approach is crest elevation, as in the case of a drop inlet ated on the berm of a dam, the adverse vortex :ential is increased. Not recommended is lo- ing the transverse antivortex wall over the vnstream endwall of the drop inlet.

tivortex Wall Height

Γhe antivortex walls were 1.5D high with one :eption: for series 611 the height of the longi- linal antivortex wall was 1.0D. The results this test can be compared with series 609 to ıluate the effect of the lower height on the :formance.

For the 1.5D wall height the vortices were all and of short duration. They admitted so .le air that there was no observable effect on ɛ headpool or on the discharge. This is shown figure XIV-12 by the open-circle data. These :a can be represented by a single line. How- ɪr, when the antivortex wall was 1.0D high, ong vortices sometimes formed after the wall :ame submerged. They caused a rise in the ıdpool level because of the reduction in discharge resulting from the replacement of water by the air admitted through the vortex core. Performance rating is therefore poor. The presence of strong vortices is shown by some of the solid-circle data in figure XIV-12. There is a wide variation in the discharge in the vicinity of $H/D = 2.25$, which results from vortices varying in strength sometimes admitting air to the spillway. This contrasts with the solid-circle data that agree with the open-circle data when the vortices do not reduce the discharge.

These tests indicate that the antivortex wall should be at least 1.5D high or should extend above the maximum anticipated headpool surface elevation if this elevation is less than 1.5D above the crest elevation.

Antivortex Wall Thickness

The effect of antivortex wall thickness can be evaluated by comparing the data obtained during series 612 where the antivortex wall was 0.333D thick with series 609 where the antivortex wall was 0.083D thick. This latter thickness was used for all other series.

Performance ratings are good for both wall thicknesses indicating, as do the recorder charts and notes taken during the tests, that such vortices as existed had no effect on the spillway performance.

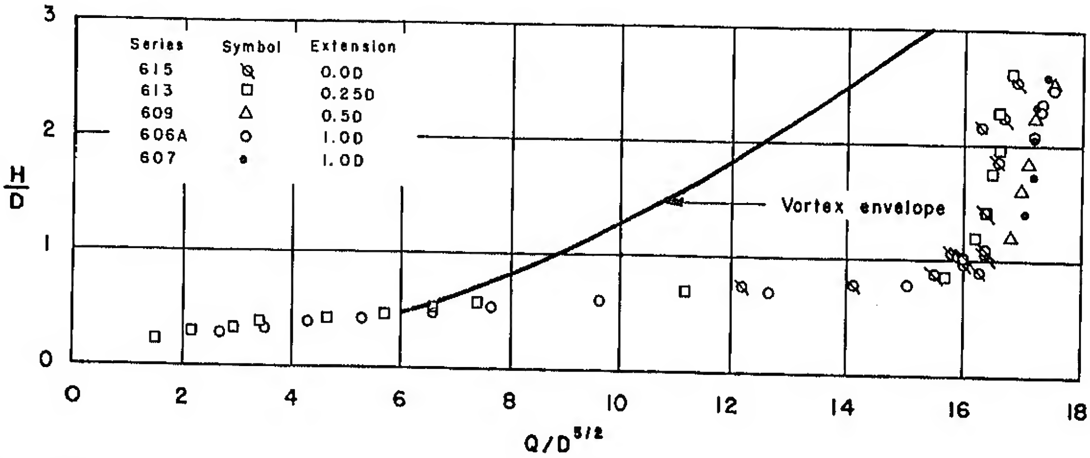


Figure XIV–13.—Head-discharge data for closed conduit spillway with 1.25D-square drop inlet showing effect of longitudinal antivortex wall extension when the approach channel is deep.

Therefore, the heads for equal discharges are higher for the greater wall thicknesses.

Antivortex Wall Extension

The length of the extension of the antivortex walls beyond the outside of the drop inlet has a significant effect on the spillway performance.

If the antivortex wall extension is too short, vortices can form at low heads. These vortices cause variations in the discharge. This is shown in figure XIV-13 for series 615 where the longitudinal antivortex wall did not extend beyond the drop inlet walls—the extension was 0D. At a relative head $H/D \approx 1.0$ there is a considerable variation in the discharge as the vortex strength varied even though the antivortex wall was not submerged. There is a further variation in the discharge after the 1.5D-high antivortex wall was submerged. This variation occurred at $H/D \approx 2.15$. Thus, the 0D antivortex wall extension did not control harmful vortices at any head, and the performance rating for series 615 is poor.

When the longitudinal antivortex wall extension was increased to 0.25D for series 613, the vortices were small and admitted air for short periods. The rating is good, and the data plotted as squares in figure XIV-13 can be used to define a single curve. The approach channel was deep. However, for the crest elevation approach depth, series 619, the rating assigned during the test was only fair to good although, as shown in figure XIV-14, the data plotted as squares define a unique head-discharge relationship.

For the longer 0.5D and 1.0D longitudinal antivortex wall extensions, series 609 and 606A and 607, the performance ratings are good, and the triangle and open- and solid-circle data plotted in figure XIV-13 define unique head-discharge relationships. The approach channel was deep for these series. When the approach floor was level with the spillway crest, the tests with the 0.5D and 1.0D antivortex wall extensions, series 616 and 617 and 620, also received a good rating. The circle and triangle data plotted in figure XIV-14 define a unique head-discharge relationship, thus verifying the assigned good rating.

Why the data for all high discharges presented in figure XIV-13 cannot be represented by a single curve is not known.

When the transverse antivortex wall was located over the downstream endwall and was extended 1.0D beyond the drop inlet sidewalls, the performance rating for both approach channel depths (series 608 and 618) was poor. The results of the series 618 tests (crest level approach) can be compared with the tests reported in Part V where the antivortex wall extension was less than 1.0D by only the drop inlet wall thickness. For the tests reported in Part V, only by preventing circulation around the antivortex wall was it possible to obtain similar head-discharge relationships. Without the dike to prevent circulation around the drop inlet, the tests reported in Part V could also be rated poor, and the rating would agree with that given the comparable more recent tests.

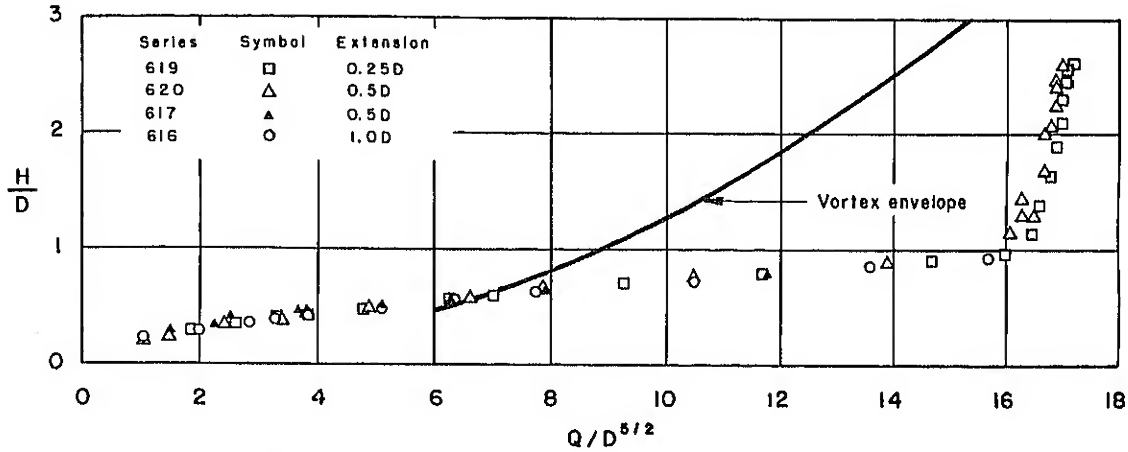


Figure XIV-14.—Head-discharge data for closed conduit spillway with 1.25D-square drop inlet showing effect of longitudinal antivortex wall extension when the approach channel floor is at crest elevation.

The data for the transverse antivortex wall located at the drop inlet midlength are plotted in figure XIV-15. For series 610 the approach was deep, and the extension was 0.5D. Its rating was good. Series 621 with a shallow approach and 0.5D extension and series 614 with a deep approach and 0.25D extension have table XIV-3 ratings of fair to good. The head-discharge relationships poorly defined by the solid triangles and squares verify that the performance ratings for series 621 and 614 should be less than good.

Even the good data for the transverse antivortex wall, denoted by open triangles in figure XIV-15, represent a less well-defined relationship at high discharges than do the corresponding open-triangle data for the longitudinal antivortex wall presented in figure XIV-13. The longitudinal antivortex wall position thus again appears superior to the transverse position.

The results of these tests indicate that the minimum extension of the antivortex wall beyond the drop inlet sidewalls should be 0.5D.

Recommendations

When the drop inlet is 1.25D square in plan, the authors recommend that:

1. The minimum depth of the drop inlet be 5.0D when the barrel entrance is square-edged.
2. The antivortex wall be located on the longitudinal centerline of the drop inlet. A transverse antivortex wall may be located at the drop inlet midlength when the approach to the drop inlet

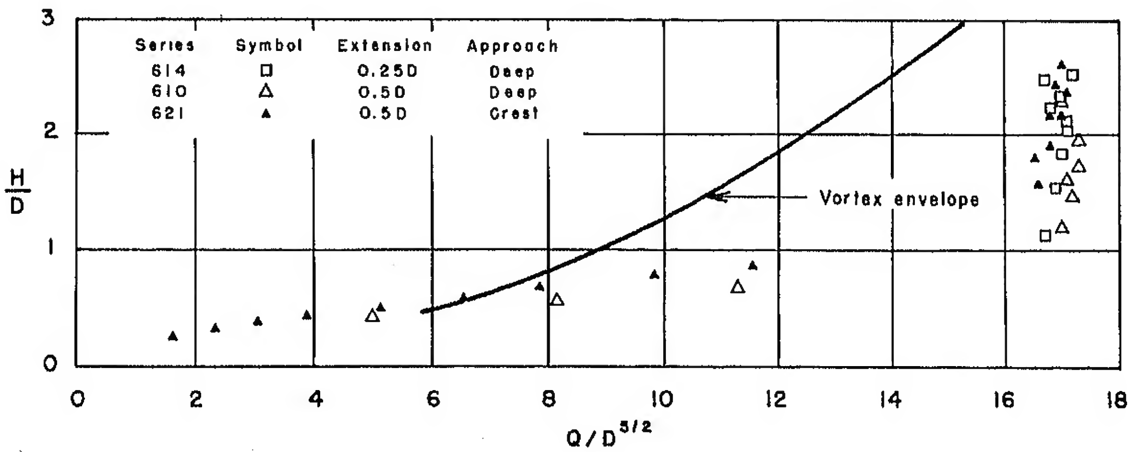


Figure XIV-15.—Head-discharge data for closed conduit spillway with 1.25D-square drop inlet showing effect of extension for transverse antivortex wall located at drop inlet midlength.

is deep, but this location is less satisfactory when the approach channel is at the drop inlet crest elevation. A transverse antivortex wall located over the downstream endwall is not recommended.

3. The minimum height of the antivortex wall be 1.5D or extend above the maximum anticipated headpool elevation, whichever is less.

4. The minimum overhang of the antivortex wall beyond the outside of the drop inlet be 0.5D.

5. The antivortex wall be as thin as structural considerations permit.

Circular Drop Inlet Antivortex Walls

Several experiments were performed on antivortex devices for circular drop inlets. The complete experiments are reported in Part VI of this series. The presentation here will be limited to a description of the models, a summary of the performance, and a listing of the recommendations pertinent to the antivortex wall part of the tests.

The Models

The types of antivortex devices tested and their dimensions are shown in figure XIV-16, adapted from figure VI-1, and table XIV-4. Additional information is given in Part VI. Pertinent differences between the various antivortex devices and drop inlets will be pointed out as the test results are presented.

Test Results

The tests reported here permit a description of the performance of various types of vortex inhibitors, but the tests were not extensive enough to determine the optimum sizes of the devices.

The test results will be presented under four general headings—longitudinal antivortex walls, cover antivortex plates, transverse tangent antivortex wall, and special antivortex device. Most of the tests were made on longitudinally oriented antivortex walls located on the drop inlet centerline, so the results of these tests will be discussed together. The horizontal cover antivortex plates will also be discussed as a group. The transverse wall and special device will be discussed separately.

Longitudinal Antivortex Walls

Longitudinal antivortex walls were used for series L-25, L-27, L-31, L-32, and L-33. There was no antivortex wall for series L-26. The test data are plotted in figure XIV-17.

As shown in figure XIV-16(a), there was no antivortex wall for series L-26. The wide scatter of the data plotted as upward-pointed triangles in figure XIV-17 at heads exceeding the weir and slug flow control range of discharges ($H/D > 1.0$) shows that an unpredictable head-discharge relationship existed when the barrel was full. This undesirable condition was due to the strong vortex action that admitted a considerable amount of air. The vortices decreased the flow until the head over the crest reached 7D. Therefore, the performance rating given in table XIV-4 for series L-26 is necessarily poor. Photographs of the vortices and a tabulation of the

TABLE XIV-4.—*Tests on the circular drop inlet*

Series	Drop inlet diameter	Antivortex wall			
		Orientation	Location	Height	Performance
L-25 ..	1.78D	Longitudinal	Centerline	0.75D	Fair to poor
L-26 ..	1.78D	None	....	....	Poor
L-27 ..	1.78D	Longitudinal	Centerline	.75D	Fair to poor
L-28 ..	1.78D	Transverse	Downstream endwall	.75D	Fair to poor
L-29 ..	1.78D	Horizontal	Cover	.75D	Good
L-29A	1.78D	Horizontal	Cover	.62D	Good
L-30 ..	1.25D	Special, see figure XIV-16(f)		1.25D	Poor
L-31 ..	1.25D	Longitudinal	Centerline	.75D	Fair to poor
L-32 ..	1.25D	Longitudinal	Centerline	.0 D	Poor
L-33 ..	1.25D	Longitudinal	Centerline	2.0 D	Good

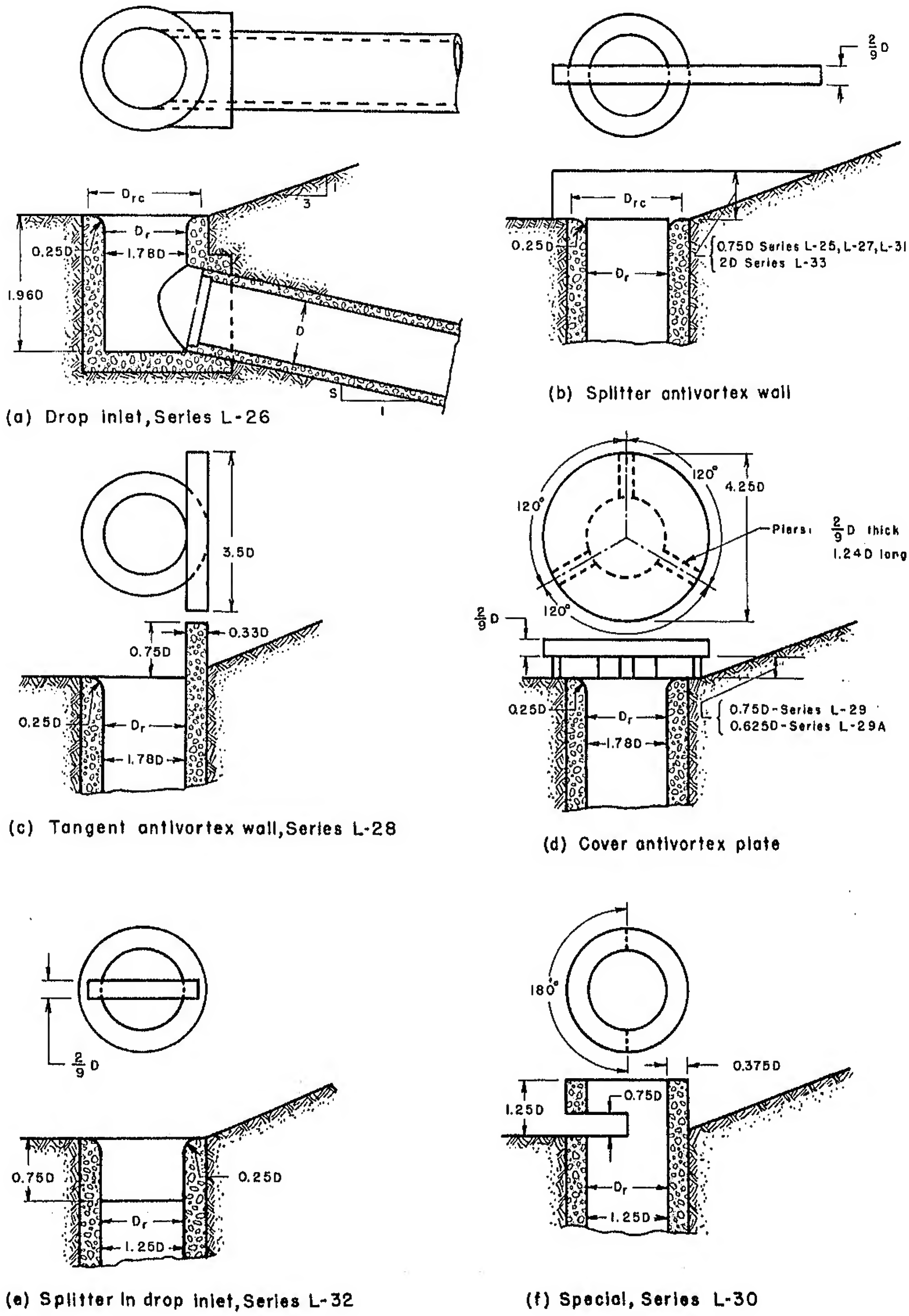


Fig. XIV-16 Drop Inlet Dimen 'tex Walls for Circular Drop Inlet.

Figure XIV-16.—Drop inlet dimensions and antivortex walls for circular drop inlet.

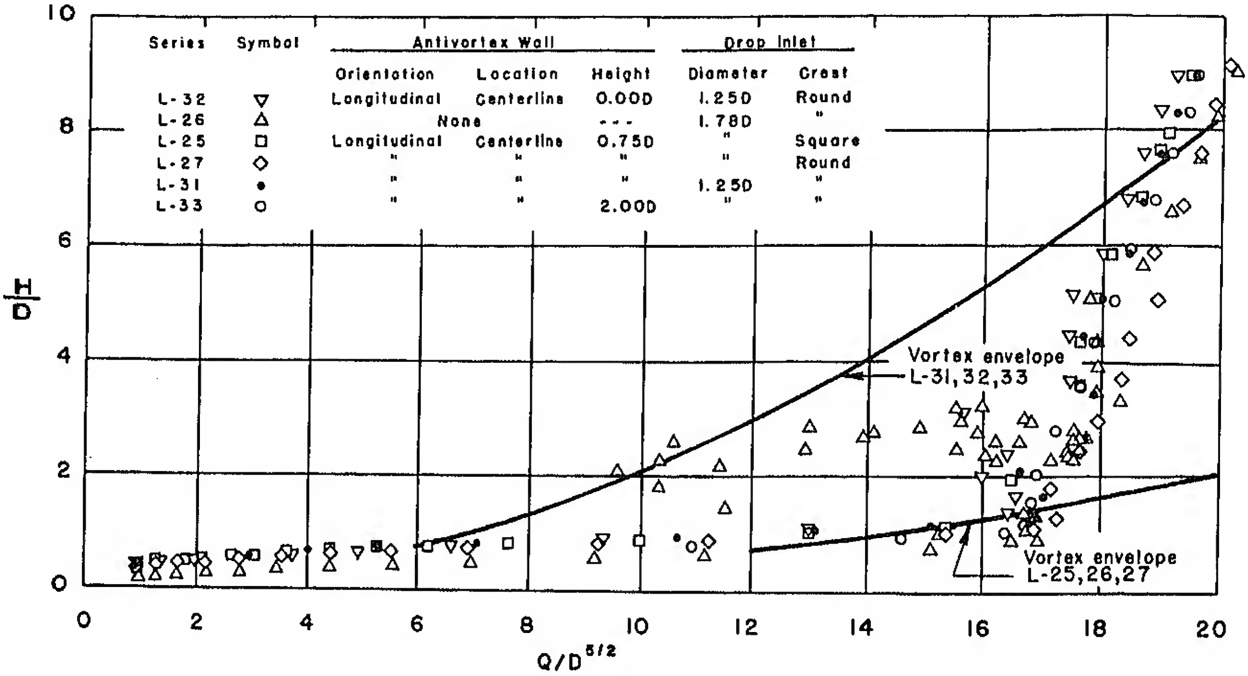


Figure XIV-17.—Head-discharge data for closed conduit spillway with circular drop inlet and longitudinal antivortex walls.

reduction in discharge caused by the vortices are shown in figure VI-2 for various heads over the drop inlet crest.

As shown in figure XIV-16(e), for series L-32 the longitudinal splitter wall extended 0.75D below the drop inlet crest; it did not extend above the crest. Again the scatter of the data plotted as downward-pointed triangles in figure XIV-17 shows that there was little control of the vortices and that the head-discharge relationship was unpredictable. The test notes state that the vortices were nearly continuous until the inlet was deeply submerged. The headpool level recorder trace was also irregular. The trace was irregular because the vortices and air caused variations in the discharge rate and consequent changes in the headpool storage and level even though the flow to the headpool was constant. Antivortex walls placed wholly within the drop inlet do not provide effective control of harmful vortices. Again, the performance rating for series L-32 is poor.

The longitudinal antivortex walls for series L-25, L-27, L-31, and L-33 shown in figure XIV-16(b) extend into the dam fill to prevent circulation around the downstream end of the wall.

For series L-25 the crest of the drop inlet was square-edged, and its effective diameter was 1.78D, the diameter of the drop inlet. For series L-27 the crest had a radius of 0.25D so the effective diameter of the crest D_{rc} is 2.28D. Because of the shorter effective crest length, the weir control data for series L-25 plotted as squares in figure XIV-17 show a slightly higher head than the data for series L-27 plotted as squares rotated 45 degrees. The head differences for full-pipe flow are much greater and indicate the significantly lower losses and larger flows obtained when the crest of the drop inlet was rounded.

The series L-25 notes indicate that vortices and air entry into the spillway were nearly continuous until the inlet was deeply submerged. Series L-27 notes state that air was admitted only at rare intervals during full-pipe flow and that, at high inlet submergences, there was no air entering the spillway. However, the full-pipe flow data for both series define an irregular head-discharge relationship so performance ratings for both series are fair to poor.

The diameter of the drop inlet was 1.25D for series L-31, L-32, and L-33. The effect of the reduced drop inlet diameter can be seen by com-

paring the data in figure XIV-17 for series L-27 where D = 1.78D (plotted as squares rotated 45 degrees) with the data for series L-31 where D = 1.25D (plotted as solid circles). For full-pipe flow there is an expected decrease in the discharge when the drop inlet diameter was reduced. For weir control there is a similar effect which shows as a slight increase in head. In addition, the weir flow heads for series L-31 (solid circles) closely agree with corresponding heads for series L-25 (squares).

This close agreement is because the effective square-edged crest diameter for series L-25 was 1.78D whereas the effective rounded crest diameter for series L-31 was 1.75D; the almost equal effective crest length should, of course, and did produce almost identical weir control head-discharge relationships. The performance rating for series L-31 is fair to poor because air entering through vortices caused the full-pipe flow data to exhibit an irregular pattern until the inlet was deeply submerged. The fair to poor performance ratings for both series L-27 and series L-31 show that there was no significant effect of drop inlet diameter on the performance.

The only difference between series L-31 and L-33 is the height of the antivortex wall—0.75D and 2.0D, respectively. Comparing the solid- and open-circle data plotted in figure XIV-17 shows that a well-defined and regular head-discharge relationship is obtained when the antivortex wall height is sufficient to control harmful vortices. Although the lower splitter wall prevented vortex formation until the wall became submerged, vortices formed after submergence of the wall and caused a reduction in the spillway capacity.

When the wall height was raised to 2.0D, vortex formation was eliminated or reduced to such an extent that any effect on the flow could not be detected. The beneficial effect of the higher wall persisted even after the higher wall was submerged. Photographs in figure VI-3 illustrate this explanation. The performance rating for the 2.0D-high wall of series L-33 is good. This is the best performance rating assigned any of the longitudinal antivortex walls.

The conclusion from these tests is that the longitudinal antivortex wall located on the drop inlet centerline will insure a unique head-discharge relationship when its height is sufficient to control harmful vortices.

Cover Antivortex Plates

The cover antivortex plate shown in figure XIV-16(d) was 4.25D in diameter and was supported on three radial piers. For series L-29 the bottom of the antivortex plate was 0.75D above the drop inlet crest. This height was reduced to 0.625D for series L-29A. The data are plotted in figure XIV-18 as upward- and downward-pointed triangles. The test notes indicate that no air entered the spillway after the initiation of full-pipe flow. The head-discharge relationships shown in figure XIV-18 are unique. As a result, the performance rating for both series L-29 and series L-29A is good.

In figure XIV-18 the head in the weir and slug flow range of discharges is lower for the lower antivortex plate height. This agrees with the findings reported for the two-way drop inlet in Part XII.

The cover antivortex device gave the best performance of any device tried on the circular drop inlets. However, the diameter of the cover was not varied and only two antivortex plate heights were tested, so the optimum dimensions are unknown. The best source of information on cover antivortex devices for circular drop inlets is the Illinois State Water Survey study reported by Humphreys, Sigurdsson and Owen.[18] On pages 8 and 9 they suggest, on the basis of a theoretical study, that the maximum needed diameter of the antivortex plate to control vortices is three times the drop inlet diameter. Additional information on their circular antivortex plate tests may be found on pages 18, 20, 28 to 31, 48 to 51, 53, 54, 56, and 62 to 63 of their publication.

Transverse Tangent Antivortex Wall

The antivortex wall tangent to the downstream side of the drop inlet is shown in figure XIV-16(c). Series L-28 was the only test conducted on the tangent wall. Water was permitted to circulate between the wall and the

[18]Humphreys, H. W., Sigurdsson, G., and Owen, H. J. Model test results of circular, square and rectangular forms of drop-inlet entrance to closed-conduit spillways. Ill. State Water Survey, Dept. Registr. Ed., State of Ill., Urbana, Rpt. Invest. 65, 70 pp., 1970.

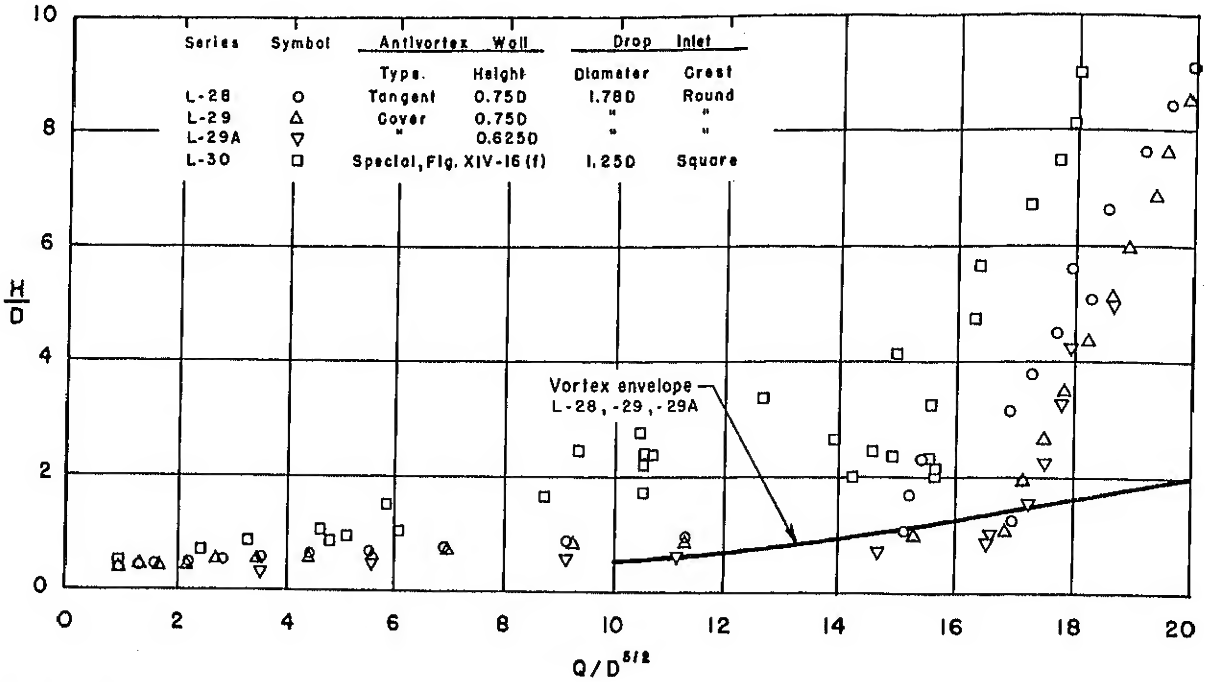


Figure XIV-18.—Head-discharge data for closed conduit spillway with circular drop inlet and cover, tangent, and special antivortex devices.

downstream end of the test channel. This aided vortex formation.

The wall height of 0.75D was found to be too low because vortices formed and admitted air continuously to the spillway until the inlet was deeply submerged. The headpool water level recorder trace was extremely irregular, and the discharge relationship was unpredictable as shown by the data plotted in figure XIV-18 as open circles. No tests were made using a higher wall. The performance rating for series L-28 is fair to poor.

Special Antivortex Device

The antivortex device shown in figure XIV-16(f) was formed by extending the drop inlet 1.25D above the drop inlet crest. The top of the drop inlet was open. A 0.75D-high opening was cut at crest level. This opening extended around 180 degrees on the upstream side of the drop inlet circumference.

The wide scatter of the data for series L-30 (plotted as squares in figure XIV-18) shows that the head-discharge relationship was unpredictable until the inlet was deeply submerged. The vortices were strong, and they continuously varied in strength. As a result, the flow through the spillway varied greatly, and the headpool level fluctuations were frequent and large. The performance rating for this antivortex device is listed as poor.

Recommendation

On the basis of performance, the cover and the splitter wall 2D high extending into the dam fill are recommended in that order. However, the difference between the performance of these two vortex inhibitors is so small that considerations other than performance should govern which antivortex device is adopted. The tangent antivortex wall might be satisfactory if its height is increased and if circulation around it is prevented. Use of the special antivortex device is not recommended.

Vortex Envelope

From tests on circular drop inlets, Humphreys and associates developed an equation for a vortex envelope curve.[14] They state, on page 26 of the publication, "The vortex had little, if any,

[14]See reference in footnote 13, p. 19.

effect on the spillway capacity for heads above the envelope." And from their summary pages 67 and 68:

> To determine when an antivortex device on a drop-inlet spillway is required for satisfactory hydraulic performance necessitates plotting . . . [the] equation . . . for the weir-flow curve, equation [XIV-4] for the vortex-envelope curve, and the full-flow curve assuming a vortex is not present. If the full-flow curve intersects the weir curve to the left of the weir curve and vortex-envelope curve intersection, the resulting head-discharge curve will be single-valued and predictable with or without an antivortex device. Conversely, if the full-flow curve intersects the weir curve to the right of the weir curve and vortex-envelope curve intersection, an effective antivortex device is needed to obtain a single-valued and predictable head-discharge curve. If an antivortex device is needed and it is not provided, the head-discharge curve composed of the weir-control curve, the vortex-envelope curve, and the full-flow curve above the vortex-envelope curve will represent the minimum performance that can be expected for a drop-inlet spillway. This method is applicable to similar prototype spillways with the drop-inlet height equal to or greater than the relative heights listed . . . .

Vortex envelope curves have been drawn on the head-discharge data plots presented in this report to see if the data presented here agree with the findings of Humphreys and associates.

Equation

The equation of the vortex envelope developed by Humphreys and associates for the circular drop inlet is

$$\frac{H}{D_r} = \frac{32}{\pi^2}\left[\frac{Q}{D_r^{5/2}\sqrt{2g}}\right]^2 \qquad \text{(XIV-1)}$$

where

- H is the head on the drop inlet crest,
- D_r is the diameter of the circular drop inlet,
- Q is the discharge, and
- g is the gravitational acceleration

Because the equation is dimensionless, any homogeneous system of units may be used. To apply this equation to their square and rectangular drop inlets a length term λ was defined as

$$\lambda = A_r/L_c \qquad \text{(XIV-2)}$$

Here

- A_r is the cross sectional area of the drop inlet, and,
- L_c is the drop inlet crest length. For the circular drop inlet

$$\lambda = \frac{\pi D_r^2}{4L_c} \qquad \text{(XIV-3)}$$

When $(4\lambda L_c/\pi)^{1/2}$ is substituted for D_r in equation XIV-1 and both sides of the equation are divided by $\lambda^{1/2}$,

$$\frac{H}{\lambda} = \frac{1}{g}\left[\frac{Q}{\lambda^{3/2}L_c}\right]^2 \qquad \text{(XIV-4)}$$

To be compatible with the coordinates used when plotting the data reported here, λ and L_c are expressed in terms of the barrel diameter D.

Comparison with Data

The data for the hood drop inlet are presented in figure XIV-2. Strong vortices obviously affected the spillway capacity until the antivortex wall was 1D high. Because the vortex-affected data plot above the vortex envelope curve, the vortex envelope curve does not define heads above which vortices will not affect the discharge through the spillway. However, the vortex envelope criteria cannot be applied because the hood drop inlet is only 2.04D high. Humphreys and associates recommend a minimum height of 4.1D to 6.5D for square drop inlets. As a result their findings agree with those presented here: an adequate antivortex device is required.

The rectangular drop inlets for figures XIV-5 and XIV-6 were 1D wide by 3D long by 4D deep, and the approaches to the drop inlets were flush with the crest and deep respectively. Humphreys and associates did not test 1D by 3D drop inlets, but for both 1D by 2D and 1D by 4D drop inlets with square-edge barrel entrances they recommend a minimum height of 5D while with a partly rounded barrel entrance they recommend a minimum height of 4D. Because strong vortices affected data that plot above the vortex envelope curve, apparently for these drop inlets the recommended minimum drop inlet height should be 5D. If 5D is accepted as the minimum drop inlet height, the vortex envelope criteria cannot be applied to the data presented in figures XIV-5 and XIV-6.

Data for 2D-long rectangular drop inlets 4D and 5D deep are shown in figure XIV-7. Some inlets that are 4D deep show vortex-affected data above the vortex envelope whereas no inlets 5D deep have vortex-affected data above the

vortex envelope curve. This further indicates that the minimum drop inlet height should be 5D if the vortex envelope criteria are to apply.

The data for 5D-long rectangular drop inlets 5D deep are shown in figure XIV-8. Although all these data fall above the vortex envelope curve, they indicate no vortex effect. Data for a 1.5D-long by 5D-deep rectangular drop inlet are shown in figure XIV-9. The data that show the effect of vortices fall below the vortex envelope. The drop inlet height criteria and the vortex envelope criteria agree with the findings of Humphreys and associates.

All the data for the square drop inlets plotted in figures XIV-11, XIV-12, XIV-13, XIV-14 and XIV-15 fall below the vortex envelope. Although these drop inlets are 1.25D square and the smallest drop inlet they tested is 1.5D square, the Humphreys and associates data indicate that vortices can be anticipated unless an adequate antivortex device is used. The data thus agree with the Humphreys and associates findings.

The data for circular drop inlets are presented in figures XIV-17 and XIV-18. Because these drop inlets are 1.96D high and the minimum height recommended by Humphreys and associates for circular drop inlets is 4.0D to 6.6D, they do not meet the minimum vortex envelope criteria, and the vortex envelope cannot be applied to these data.

Conclusions

The data presented here generally verify the finding of Humphreys and associates that head-discharge relationships falling above their vortex envelope are predictable. An important limitation to note is that the vortex envelope criteria can be applied only if the drop inlet height equals or exceeds the Humphreys and associates recommended minimum height—a height that is greater than for most of the comparisons reported here.

General Conclusions

These tests, like other tests, have shown that harmful vortices can be expected at drop inlets to closed conduit spillways if there is no device to inhibit their formation. The vortices admit air to the spillway, reduce its capacity, and vary in intensity so much that a predictable, unique head-discharge relationship cannot be assured. Some type of antivortex device is required to assure that the spillway discharge and performance can be predicted.

The cover antivortex device used on the circular drop inlet apparently is the most effective of the forms reported herein. More extensive investigations of the cover antivortex plate are reported for the two-way drop inlet in Part XII and for circular drop inlets by Humphreys and associates.

The longitudinal antivortex wall located on the drop inlet centerline proved an effective antivortex device for all forms of the drop inlet. The recommended minimum heights of the wall for the drop inlets tested are 1D for the hood and rectangular drop inlets, 1.5D for the square drop inlet, and 2D for the circular drop inlet. The extension of the wall outside the drop inlet was 0D for the hood drop inlet, D/2 for the rectangular drop inlet, and D/2 upstream and into the dam fill downstream for the circular drop inlet.

The most effective location of a transverse antivortex wall for the rectangular drop inlet is one-third the drop inlet length upstream from the downstream endwall. For the square drop inlet the most effective location is at its midlength, but the midlength location is not satisfactory for the rectangular drop inlet. Transverse antivortex walls located over the downstream endwall of the drop inlet are not recommended for the rectangular and square drop inlets.

A transverse antivortex wall tangent to the downstream side of the circular drop inlet may be satisfactory only if circulation around it is prevented. The minimum height of the tangent antivortex wall for the circular drop inlet is probably 2D; but, because vortices may form if the antivortex wall is submerged, it is desirable that the antivortex wall extend to the maximum water surface elevation. The overhang of the antivortex walls beyond the drop inlet sidewalls is D/2 for the rectangular and square drop inlets. The antivortex wall tangent to the downstream edge of the circular drop inlet was 3.5D long.

Acknowledgments

Consultation was continuous with Soil Conservation Service (SCS) engineers throughout the planning and conducting of these tests. The primary SCS contact was through M. M. Culp, chief, Design Branch, Engineering Division, SCS, Washington, D.C., and his significant contributions are especially appreciated.

The circular drop inlet tests were initiated in 1951 at the request of A. F. Moratz, head, District Operations Design and Construction, SCS, Milwaukee, Wis., to see if antivortex walls would be required for the circular cast-in-place drop inlet being used by SCS agricultural engineer Charles Dickerson near Warrensburg, Mo. Moratz suggested the antivortex wall type in figures XIV-16(b) and (f). Tests on the antivortex device in figure XIV-16(e) were requested by Edwin Freyburger, regional engineer, SCS, Milwaukee, Wis., to see if this wall would effectively control vortices and would make unnecessary the walls extending above the drop inlet crest. The cover plate antivortex device in figure XIV-16(d) was suggested by M. M. Culp when he was head, Engineering Standards Unit, SCS, Lincoln, Nebr. Culp's initial correspondence of July 6, 1951, shows an excellent understanding of the important hydraulic design criteria and performance of the cover antivortex plate as later tests defined them.

The tests reported here were performed by Charles A. Donnelly, who also evaluated the performance of the antivortex walls and wrote the initial drafts of this report. Fred W. Blaisdell directed the study, completed the analyses, and wrote the final draft.

Hydraulics of Closed Conduit Spillways

Part XV: Low-Stage Inlet for the Two-Way Drop Inlet

By CHARLES A. DONNELLY and FRED W. BLAISDELL[15]

Introduction

Drop inlets for closed conduit spillways have been discussed in several parts of this series of reports. Sometimes it is desirable to add one or more low-stage inlets[16] to the two-way drop inlet as shown in figure XV-1. The principal spillway entrance is then called a two-stage drop inlet.

The principal uses and advantages of the two-stage inlet have been presented by M. M. Culp:[17]

> 1 In upstream flood prevention work the structure may be proportioned so that all floods up to those of a specific frequency are regulated by the low-stage orifice, or so that sufficient volume of the flood will be delayed by the storage between the low and the high-stage inlets that the peak discharge from the uncontrolled area below the retarding dams will pass successive downstream reaches before the increase in discharge through the high-stage inlet gets to these same successive reaches where damage is to be reduced.
>
> These design procedures result in more economical proportioning of retarding dams . . . .
>
> 2 The second principal use of the two-stage inlet is in connection with the design of retarding dams placed above channels that are unstable and eroding . . . .
>
> 3 Another advantage of the two-stage inlet is that its use permits the safe use of a covered inlet . . . .

Regarding the low-stage inlet, Culp says:

> (a) The crest elevation of the low-stage inlet is established to provide the required sediment storage, plus any additional storage needed in the reservoir for beneficial use.
>
> (b) The capacity and size of the low-stage inlet . . . is determined to satisfy downstream flood control, or stream-channel stability requirements.

Originally there was no anticipated need to test the low-stage inlet used with the two-way drop inlet. This is because no problems were anticipated regarding the spillway performance as a result of the performance of the low-stage inlet, and because the capacity of the low-stage inlet could be determined with sufficient accuracy by using handbook weir and orifice discharge coefficents. However, in a working model of the two-way drop inlet built for demonstration purposes, the jet issuing from the low-stage orifice located in the upstream endwall of the drop inlet shot across the length of the drop inlet and hindered filling (priming) of the conduit.

The series of photographs of figure XV-2 shows the jet issuing from the orifice and the action in the drop inlet and in the barrel entrance as the reservoir level rises. This impairment of the spillway performance noted in the demonstration model, which does not occur when the orifice is closed (fig. XV-2(e)), cannot be tolerated in the prototype; this unacceptable performance is the reason tests were made on the low-stage inlet for the two-way drop inlet.

The test results show that the low-stage inlets in two-way drop inlets must be located properly to insure satisfactory performance. Poor performance occurred when the width of the low-stage inlet was equal to the width of the drop

[15] See footnote 1, p. 1.

[16] The words "inlet," "entrance," and "orifice" are used interchangeably in this Part.

[17] Culp, M. M. Two-stage [illegible] lets. Agr. [illegible] 960.

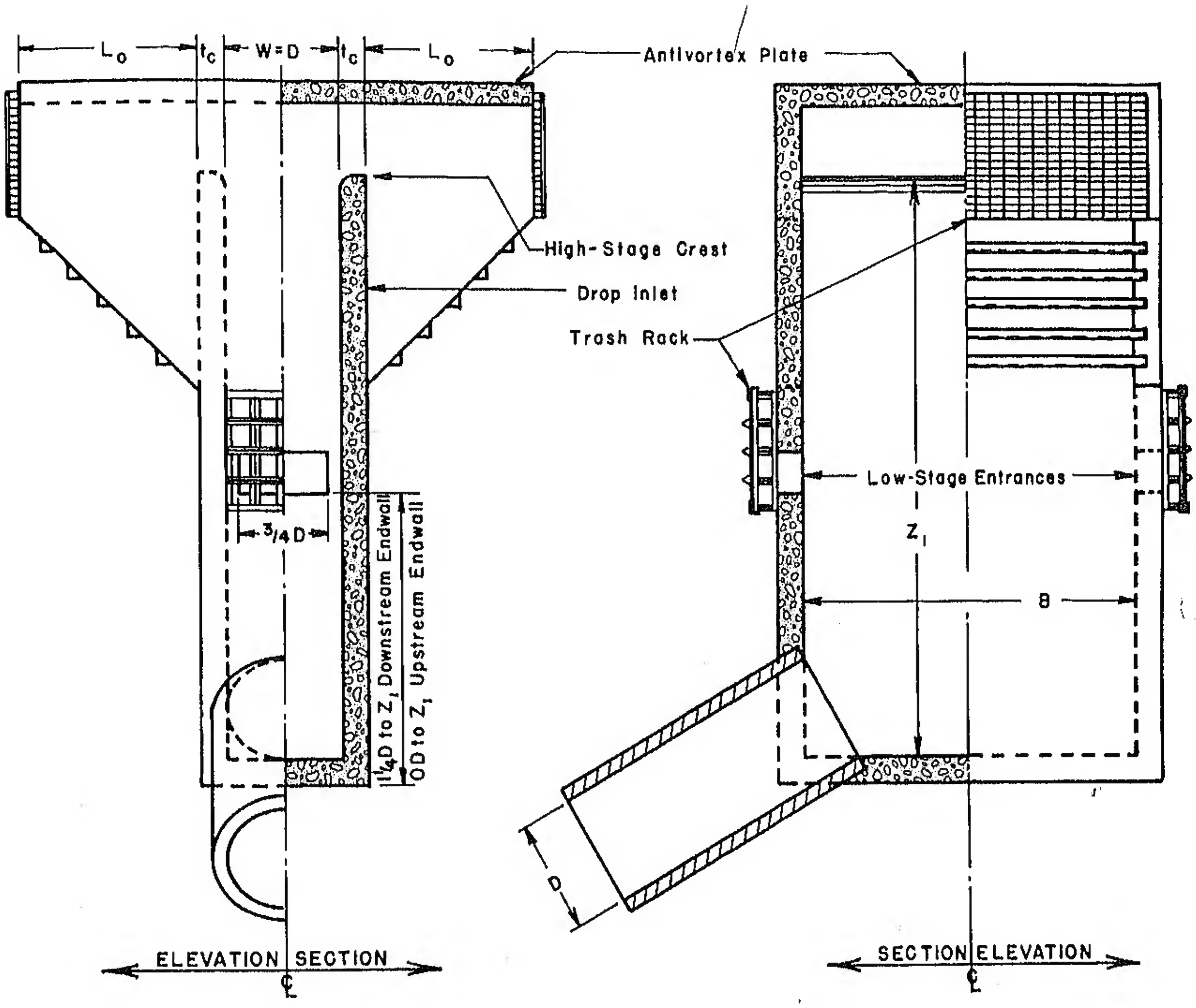


Figure XV-1.—Two-stage, two-way drop inlet closed conduit spillway entrance.

inlet. Satisfactory performance was obtained when the width of the low-stage inlet was three-fourths the width of the drop inlet. The low-stage inlets may be located at any elevation in either one or both drop inlet endwalls, but not in the drop inlet sidewalls.

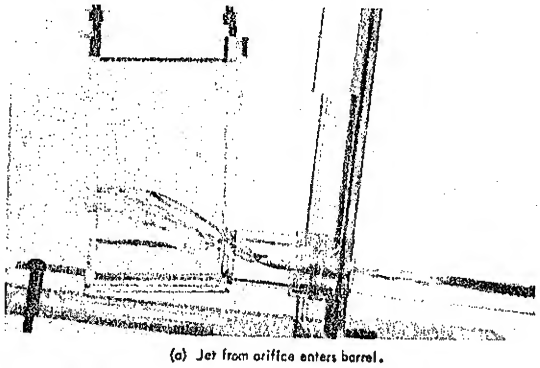
Details of the tests are presented in the following section.

The Tests

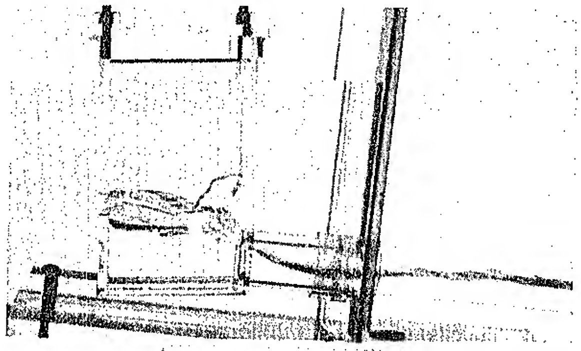
The tests were performed using the water apparatus and, in general, the procedure and analytical methods described in Part X. Necessary modifications were made to obtain the information required for this study of the low-stage inlets.

The two-way drop inlets were 6D high ($Z_l/D = 6.0$), 1D wide ($W/D = 1.0$), and 2D or 3D long ($B/D = 2.0$ or 3.0). The antivortex plate was 0.8D ($Z_p/D = 0.8$) above the drop inlet crest, and thus it had no effect on the performance when the low-stage orifice controlled the head-discharge relationship. The antivortex plate overhang was 2D ($L_o/D = 2$). The drop inlet walls were 1/4-inch-thick plastic ($t_c/D = 0.111$). The conduit diameter D was 2.25 inches. The barrel slope S was 20 percent for all tests.

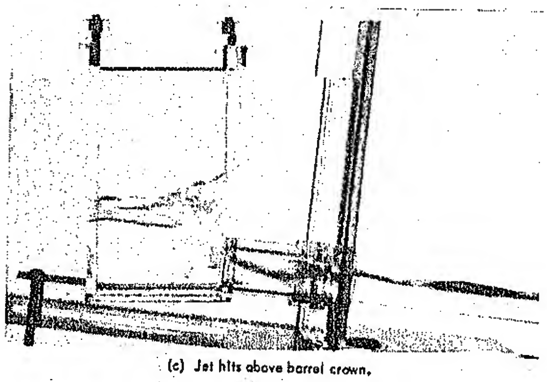
The tests were planned to determine how the location of the low-stage inlet affected the spillway performance. The inlet orifice was located, for the various test series, at several elevations in each of the drop inlet walls. The elevations of



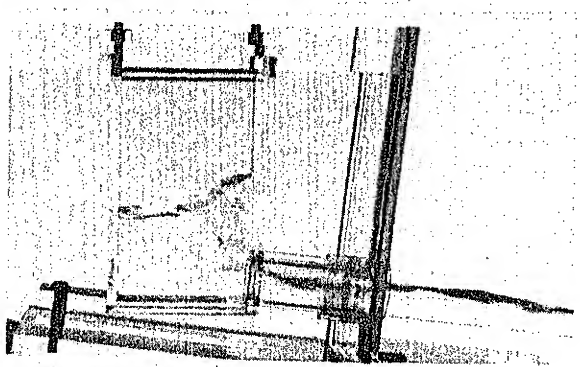
(a) Jet from orifice enters barrel.



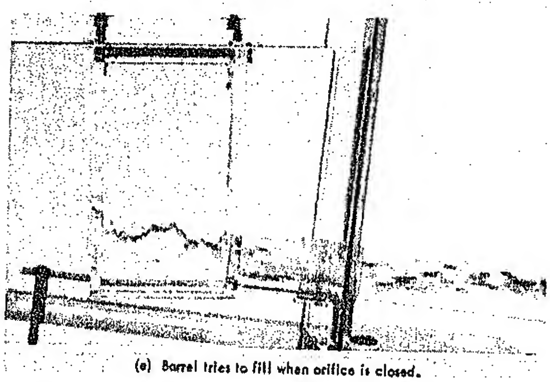
(b) Top of jet hits barrel crown.



(c) Jet hits above barrel crown.



(d) Jet from orifice prevents barrel from filling even with flow over high-stage crest.



(e) Barrel tries to fill when orifice is closed.

Figure XV-2.—Jet from low-stage orifice prevents barrel from filling when the orifice is 1D wide. Demonstration model barrel diameter is 1 inch. Drop inlet is 1D wide by 3D long by 5D deep. Orifice crest is 1.5D above drop inlet floor.

the orifice crest above the drop inlet floor were 0D, 1D, 2D, 3D, 4D and 5D when the orifice was in the upstream endwall and the sidewalls; when the orifice was in the downstream endwall, the orifice crest elevations were 1.25D, 2.25D, 3.25D, 4.25D and 5.25D.

The maximum practical area of the low-stage inlet was anticipated to be somewhat less than the area of the barrel so that the low-stage inlet rather than the barrel would control the head-discharge relationship. The initial orifice size was therefore set at D wide by D/2 high. Its area, $D^2/2$, is 64 percent of the barrel area, $\pi D^2/4$. Later the orifice was made 3D/4 square. This area, $9D^2/16$, is 72 percent of the barrel area. Although two orifices were sometimes used, one of their dimensions was halved so the aggregate orifice area remained the same. Orifices having a lesser area were not tested. This is because of the unverified assumption that smaller inlet orifices would have less effect on the spillway performance. All orifices had square edges.

Head-discharge data sufficient to evaluate the effect of the low-stage inlet on the spillway performance were obtained for all test series. The spillway performance was observed and recorded. Photographs and movies were sometimes taken.

The test program included 53 series of tests. These series and the geometry of each inlet are listed in table XV-1.

Table XV-1.—*Summary of tests*

$Z_1/D = 6.0$ $t_c/D = 0.111$ $Z_p/D = 0.8$ $L_o/D = 2.0$ $S = 0.20$

Series	B/D	Orifice size Width	Orifice size Height	Orifice location[1] Elevation[2]	Orifice location[1] Wall	Notes on performance
W-553	.3	1.00D	0.500D	0.00D	Upstream endwall	Good, noisy
W-554	.3	1.00D	.500D	1.00D	Upstream endwall	Good, noisy
W-555	.3	1.00D	.500D	2.00D	Upstream endwall	Good, noisy
W-556	.3	1.00D	.500D	3.00D	Upstream endwall	Orifice[3, 4]
W-557	.3	1.00D	.500D	4.00D	Upstream endwall	Good
W-558	.3	1.00D	.500D	2.00D	Upstream endwall	Good
W-559	.3	1.00D	.500D	3.00D	Upstream endwall	Orifice[3]
W-560	.3	1.00D	.500D	1.25D	Downstream endwall	Violent action[5]
W-561	.3	1.00D	.500D	2.25D	Downstream endwall	Flapping jet
W-562	.3	1.00D	.500D	3.25D	Downstream endwall	Flapping jet
W-563	.3	1.00D	.500D	4.25D	Downstream endwall	([6])
W-564	.3	1.00D	.500D	5.25D	Downstream endwall	([6])
W-565	.3	1.00D	.500D	1.00D	Right sidewall[7]	Turbulence
W-566	.3	1.00D	.500D	2.00D	Right sidewall[7]	([8])
W-567	.3	1.00D	.500D	3.00D	Right sidewall[7]	Bad turbulence
W-568	.3	1.00D	.500D	4.00D	Right sidewall[7]	Bad turbulence
W-569	.3	1.00D	.500D	5.00D	Right sidewall[7]	Bad turbulence
W-570	.3	1.00D	.500D	.00D	Right sidewall[7]	
W-571	.3	.50D	.500D	1.00D	Both sidewalls[7]	Orifice[3]
W-572	.3	.50D	.500D	2.00D	Both sidewalls[7]	([9])
W-573	.3	.50D	.500D	3.00D	Both sidewalls[7]	([9])
W-574	.3	.50D	.500D	4.00D	Both sidewalls[7]	Orifice[3]
W-575	.3	.50D	.500D	5.00D	Both sidewalls[7]	([9])
W-576	.3	.50D	.500D	.00D	Both sidewalls[7]	Turbulence
W-577	.3	.75D	.750D	.00D	Upstream endwall	Good
W-578	.3	.75D	.750D	1.00D	Upstream endwall	Good
W-579	.3	.75D	.750D	2.00D	Upstream endwall	Good
W-580	.3	.75D	.750D	3.00D	Upstream endwall	Good
W-581	.3	.75D	.750D	4.00D	Upstream endwall	Good
W-582	.3	.75D	.750D	5.00D	Upstream endwall	Good

Series	B/D	Orifice size Width	Orifice size Height	Orifice location[1] Elevation[2]	Orifice location[1] Wall	Notes on performance
W-583	.3	0.75D	0.750D	1.25D	Downstream endwall	Good, quiet
W-584	.3	.75D	.750D	2.25D	Downstream endwall	Good, quiet
W-585	.3	.75D	.750D	3.25D	Downstream endwall	Good, quiet
W-586	.3	.75D	.750D	4.25D	Downstream endwall	Good, quiet
W-587	.3	.75D	.375D	1.25D	Both endwalls	Good, quiet
W-588	.3	.75D	.375D	2.25D	Both endwalls	Good, quiet
W-589	.3	.75D	.375D	3.25D	Both endwalls	Good, quiet
W-590	.3	.75D	.375D	4.25D	Both endwalls	Good, quiet
W-591	.3	.75D	.375D	([10])	Both endwalls	Good, quiet
W-592	.2	.75D	.750D	.00D	Upstream endwall	Good, quiet
W-593	.2	.75D	.750D	1.00D	Upstream endwall	Good, quiet
W-594	.2	.75D	.750D	2.00D	Upstream endwall	Good, quiet
W-595	.2	.75D	.750D	3.00D	Upstream endwall	Good, quiet
W-596	.2	.75D	.750D	4.00D	Upstream endwall	Good, quiet
W-597	.2	.75D	.750D	1.25D	Downstream endwall	Good
W-598	.2	.75D	.750D	2.25D	Downstream endwall	Good, quiet
W-599	.2	.75D	.750D	3.25D	Downstream endwall	Good, quiet
W-600	.2	.75D	.750D	4.25D	Downstream endwall	Good, quiet
W-601	.2	.75D	.375D	([10])	Both endwalls	Good, quiet
W-602	.2	.75D	.375D	1.25D	Both endwalls	Good, quiet
W-603	.2	.75D	.375D	2.25D	Both endwalls	Good, quiet
W-604	.2	.75D	.375D	3.25D	Both endwalls	Good, quiet
W-605	.2	.75D	.375D	4.25D	Both endwalls	Good, quiet

[1] Location in drop inlet.
[2] Crest elevation above drop inlet floor.
[3] The flow control at the barrel entrance was orifice.
[4] Orifice flow increased the head 0.11H/D, then the barrel primed.
[5] Flow in the pipe near the drop inlet was violent.
[6] Jet flapping imminent.
[7] At upstream end of drop inlet.
[8] High boil in the drop inlet.
[9] Turbulence and high water in drop inlet.
[10] At 0.00D in upstream endwall and 1.25D in downstream endwall.

Test Results

The results of the tests will be discussed under the broad headings Spillway Performance and Orifice Capacity. The tests were made primarily to evaluate the effect of the low-stage inlet on the spillway performance. In addition, such information as can be gleaned from the capacity analysis will be presented.

Spillway Performance

Because the rectangular orifices exhibited less satisfactory performance than did the square orifices, the performance test results will be presented under two headings—Orifices 1D Wide by D/2 High and Orifices 3D/4 Square.

Orifices 1D Wide by D/2 High

Orifices in endwalls.—The low-stage inlets initially recommended by SCS were shown on their standard drawings to be equal in width to the drop inlet width and to have a height as required but not less than 6 inches. For two-way and rectangular open-top drop inlets, the orifice could be located in either endwall; for square open-top drop inlets, the orifice could be in any wall. No limits were placed on the elevation of the orifice crest, this elevation being determined by the project storage requirements.

The first two groups of test series were made on the two-way drop inlet to check the SCS recommendations: The first group had the orifice in the upstream endwall and the second group had the orifice in the downstream endwall. In each group the orifice crest elevation was varied.

When the 1D by D/2 rectangular orifice was in the upstream endwall, the performance was rated good for the orifices 0D, 1D, 2D and 4D above the drop inlet floor. This is shown in table XV-1 for series W-553, W-554, W-555 and W-557. However, for one of the ten test flows used during series W-556, where the orifice crest was 3D above the drop inlet floor, the barrel entrance acted as an orifice and the barrel was not full. Slugs of water in the barrel at lesser or greater flows indicated that the barrel would not fill (prime).

Check tests with orifice crest elevations of 2D (series W-558) and 3D (series W-559) verified the performance originally observed during series W-555 and W-556. Notes taken during series W-559 indicate that the barrel would prime if the nappes from the high-stage inlet weir spring free from the drop inlet sidewalls. On the other hand, the notes say that priming is hindered when the high-stage weir nappes cling to the drop inlet sidewalls. When the orifice was closed, the barrel primed with the high-stage weir nappes both clinging and free, thus indicating that the flow from the low-stage inlet rather than the condition of the nappes inhibits priming of the barrel. Why the poor performance occurs only for the low-stage orifice crest elevation of 3D above the drop inlet floor is not apparent.

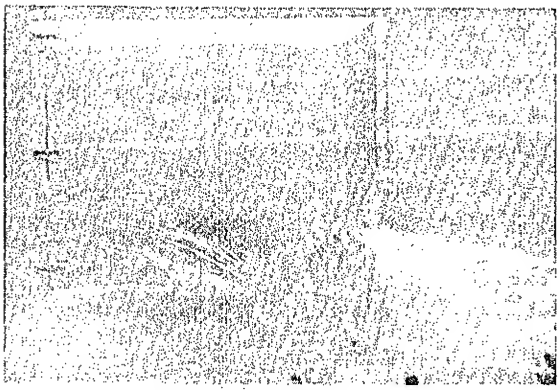
Pertinent to note is that these tests qualitatively verify the poor performance observed on the demonstration model which was 1:2.25 the size of the spillway tested. The verification is qualitative because the low-stage inlet orifice elevation was 1.5D in the demonstration model and 3D for the similar poor performance observed during the tests reported here.

Photographs taken during the tests show the action of the flow near the bottom of the drop inlet and in the barrel near its entrance. Figure XV-3 shows the jet trajectory and the flow conditions near the drop inlet base and barrel entrance. (Q is the discharge in cubic feet per second, D is the barrel diameter in feet, and H_o is the head on the crest (bottom edge) of the orifice.) The photographs were selected from those available to have nearly the same discharge and to have a low discharge so the jet trajectory would not be hidden by the water in the drop inlet.

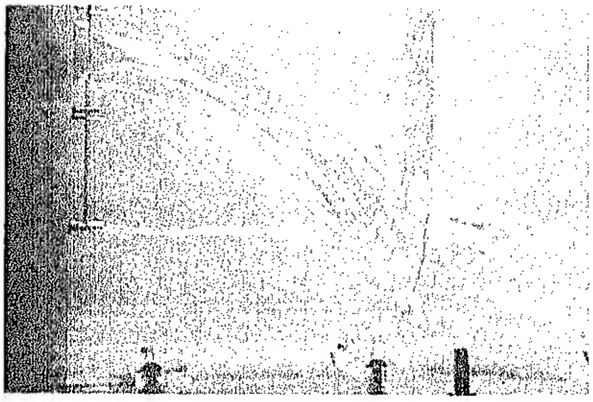
When the orifice is flush with the bottom of the drop inlet, the jet crosses the drop inlet and enters the barrel smoothly (fig. XV-3(a)). When the orifice crest elevation increases, the jet for the same discharge progressively impinges on the floor at greater distances from the upstream endwall (fig. XV-3(b)), plunges into the barrel entrance (fig. XV-3(c)), and impinges on the downstream wall at increasingly greater heights (figs. XV-3(d) and XV-3(e)).

The performance at increasing discharges is shown in figure XV-4 for an orifice elevation of 2D (series W-555). In figure XV-4(a) the jet penetrates the water surface in the drop inlet at

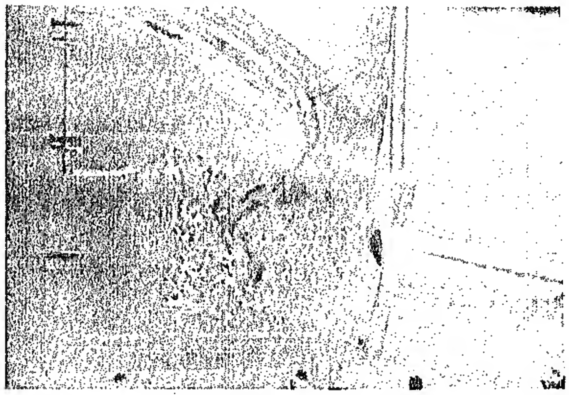
(a) Orifice elevation = 0 D;
$Q/D^{5/2}$ = 3.87; H_o/D = 2.50;
Series W-553.



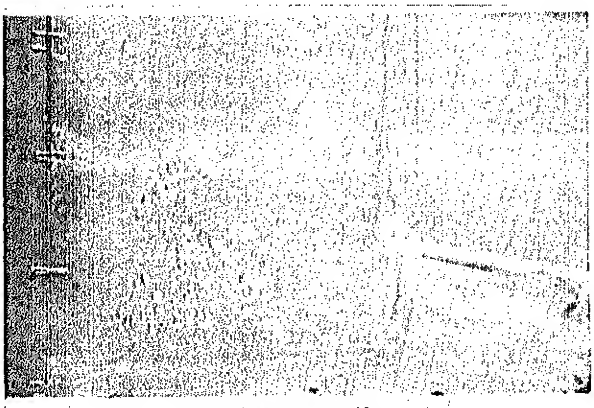
(b) Orifice elevation = 1 D;
$Q/D^{5/2}$ = 3.28; H_o/D = 1.86;
Series W-554.



(c) Orifice elevation = 2 D;
$Q/D^{5/2}$ = 3.17; H_o/D = 1.72;
Series W-555.



(d) Orifice elevation = 3 D;
$Q/D^{5/2}$ = 3.14; H_o/D = 1.70;
Series W-556.



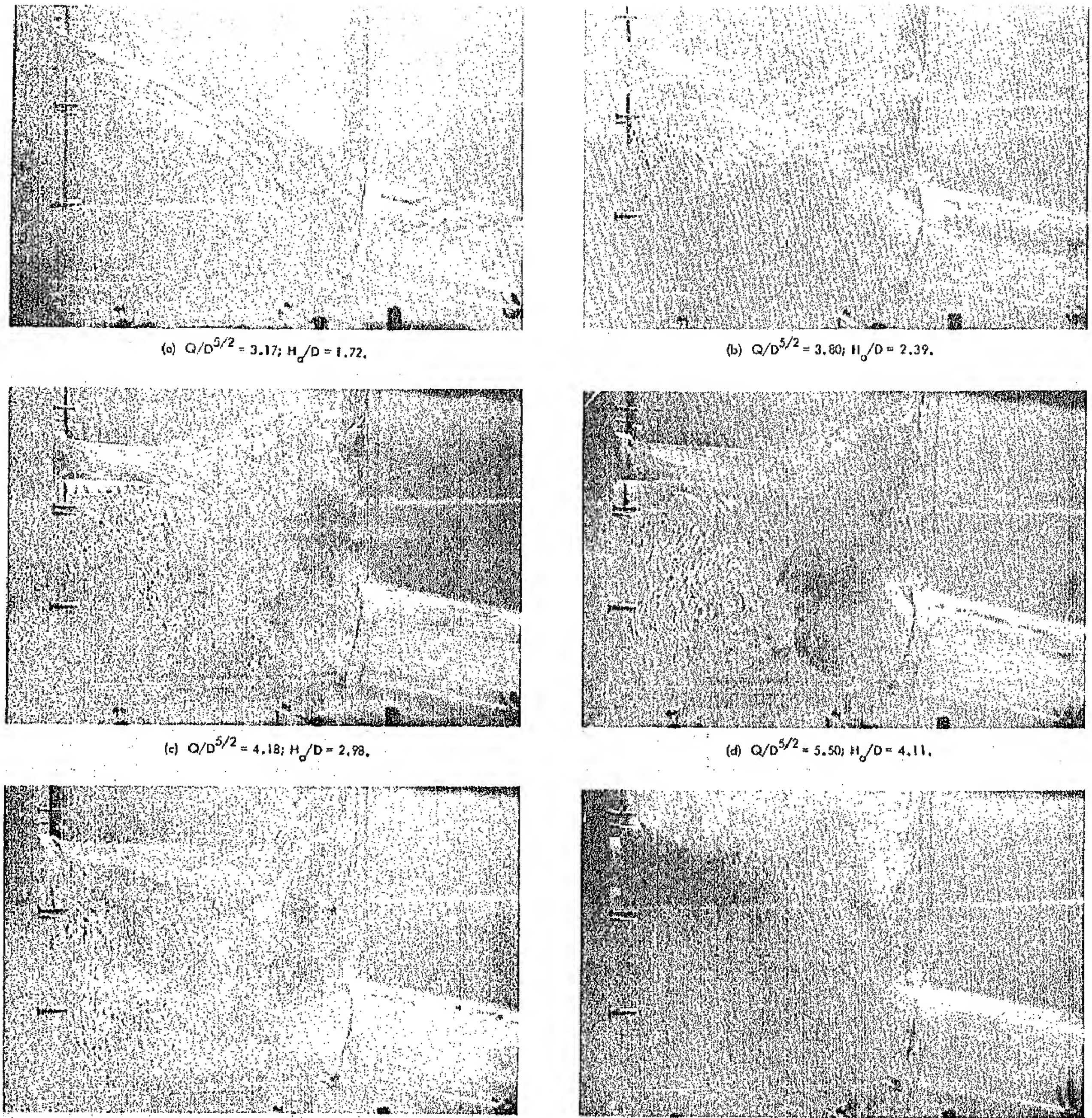
(e) Orifice elevation = 4 D;
$Q/D^{5/2}$ = 2.25; H_o/D = 0.90;
Series W-557.

Figure XV-3.—Trajectory from 1D by D/2 rectangular low-stage orifices in upstream endwall and flow in bottom of drop inlet and in barrel entrance for several low-stage orifice crest elevations.

a steep angle and lands in the barrel entrance.

In figure XV-4(b) the water in the drop inlet supports the jet so it strikes the downstream wall of the drop inlet close to the pipe crown. A boil rides between the jet and the downstream wall.

In figure XV-4(c) the water level in the drop inlet is close to the orifice elevation. The jet is supported for most of its travel across the drop inlet, is deflected downward only a little, and strikes the downstream wall well above the barrel entrance. The boil rises to an elevation higher than the orifice.



(a) $Q/D^{5/2} = 3.17$; $H_o/D = 1.72$.

(b) $Q/D^{5/2} = 3.80$; $H_o/D = 2.39$.

(c) $Q/D^{5/2} = 4.18$; $H_o/D = 2.98$.

(d) $Q/D^{5/2} = 5.50$; $H_o/D = 4.11$.

(e) $Q/D^{5/2} = 7.15$; $H_o/D = 4.22$.

(f) $Q/D^{5/2} = 16.17$; $H_o/D = 4.55$.

Figure XV-4.—Trajectory from 1D by D/2 rectangular low-stage orifice in upstream endwall and flow in bottom of drop inlet and in barrel entrance for several discharges. B = 3D; orifice elevation = 2D; series W-555.

In figure XV-4(d) the action shown in figure XV-4(c) is intensified. The depth of flow over the high-stage weir crest is now 0.11D, and the weir nappes appear to cling to the sides of the drop inlet. The flow is greater for figure XV-4(e), but the action seems to be much the same as figure XV-4(d). In figure XV-4(f) the drop inlet is nearly full and the orifice jet is fully supported.

As mentioned previously when discussing series W-556, the barrel entrance can act as an orifice to control the flow. This is illustrated in

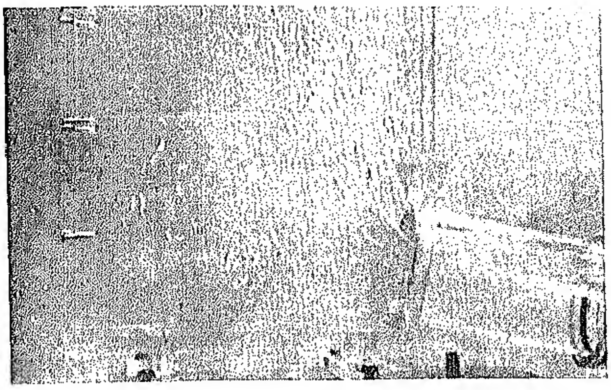


Figure XV-5.—The barrel entrance is acting as an orifice and the barrel is part full. Orifice elevation = 3D; $Q/D^{5/2} = 9.62$; $H_s/D = 3.39$; series W-556.

figure XV-5. In contrast to the previous pictures, the barrel is only partly full and the flow in the drop inlet is much slower and less violent. The head over the high-stage weir crest is 0.39D, and the drop inlet is almost full.

The previous discussion has concerned the 1D by D/2 rectangular low-stage orifice located in the upstream endwall of the two-way drop inlet. The following discussion concerns the performance of this orifice when it is located in the downstream endwall.

Because the barrel leaves the drop inlet through the downstream endwall, the minimum possible elevation of the orifice crest is 1D. The minimum practical elevation of the orifice crest is somewhat higher. For these tests the minimum elevation was 1.25D. The crest elevation was 1.25D, 2.25D, 3.25D, 4.25D, and 5.25D for successive test series as shown in table XV-1.

When the 1D-wide by D/2-high rectangular drop inlet was in the downstream endwall, the spillway performance was poor. The primary reason for the poor performance is that the jet from the orifice occupies the full width of the drop inlet. This provides a water curtain between the drop inlet crest and the barrel entrance and seals the barrel entrance from the nappes falling from the high-stage crest.

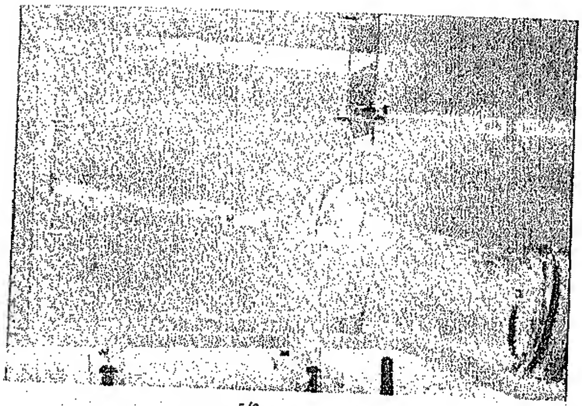
As slugs form and pass through the barrel, lower pressures develop near the barrel entrance, a demand for air is created to relieve the lower pressure, and the nappe is deflected downward until it breaks. As the slug breaks or leaves the barrel, the pressure at the barrel entrance rises, and the nappe also rises. The fluctuating nappe was taken to indicate an undesirable flow condition. In contrast to the orifice located in the upstream endwall, there was no indication that the barrel would not prime, although priming was inhibited.

Various flow conditions when the 1D by D/2 rectangular low-stage orifice in the downstream endwall has its crest 1.25D above the drop inlet floor are shown in figure XV-6. In figure XV-6(a) the barrel is full of a mixture of water and air for a short distance and there is some airflow. The jet from the orifice is depressed, and it makes a sharp turn to enter the barrel. Figures XV-6(b) and XV-6(c) illustrate a higher discharge and show flow conditions in the drop inlet without and with air flowing continuously through the barrel. The bubbles in the water in the drop inlet show the high turbulence. In addition to the flow through the low-stage orifice, there is flow from a head of 0.28D over the high-stage crest. The flapping nappe is shown in figure XV-7. There is no flow over the high-stage weir crest.

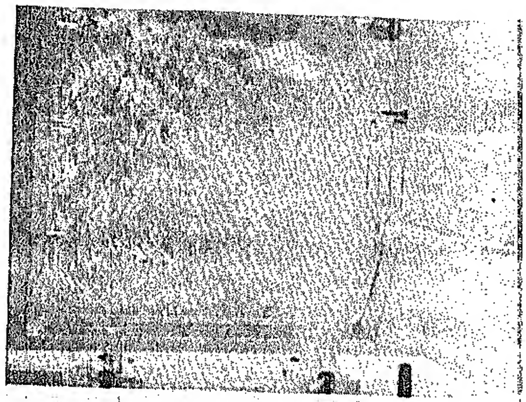
Orifices in sidewalls.—Because of the poor performance of the 1D by D/2 rectangular low-stage inlet when located in the drop inlet endwalls, tests were made with the orifice located in one sidewall and at the upstream end of the 3D-long drop inlet. Few observation notes and no photographs were taken during these tests (series W-565 through W-570 in table XV-1). The notes taken indicated that the barrel primed but there was excessive and asymmetrical turbulence in the drop inlet. The overall performance of the 1D by D/2 rectangular low-stage orifice located at the upstream end of one of the drop inlet sidewalls was considered unsatisfactory.

For the next group of tests the length of the low-stage inlet was halved, and one half was placed in the upstream end of each sidewall. The resulting orifices were D/2 square and opposed each other. These tests are listed in table XV-1 as series W-571 through W-576. In general, the flow conditions in the drop inlet were poor. In figure XV-8(a) the barrel entrance acting as an orifice sometimes controlled the flow for the 1D- (series W-571) and 4D-elevations (series W-574) of the low-stage inlets above the drop inlet bottom.

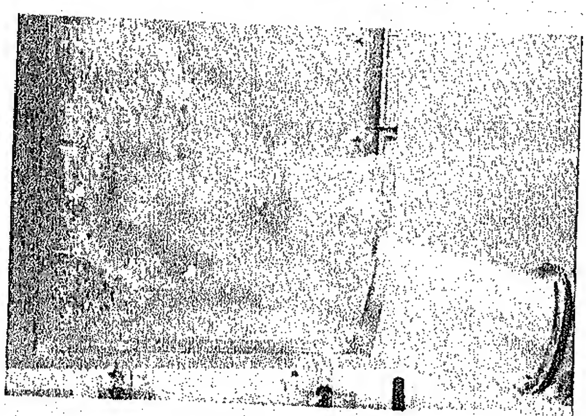
A special note indicates that the barrel primed for the 3D inlet elevations (series W-573); lack of contrary notes leads to the assumption that



(a) $Q/D^{5/2} = 2.90$; $H_o/D = 1.22$.
Specks are air bubbles on outside of drop inlet.



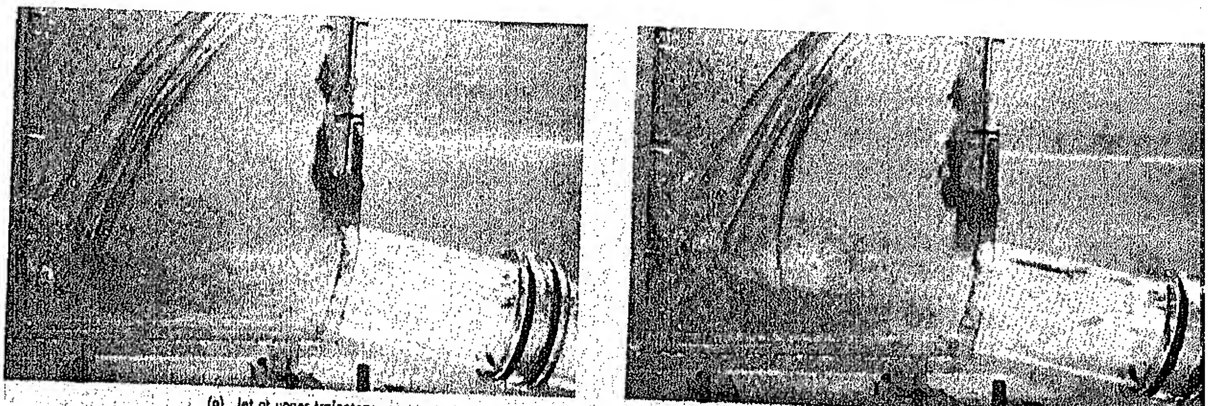
(b) $Q/D^{5/2} = 10.27$; $H_o/D = 5.03$.
No air being sucked. 0.28D head on high-stage crest.



(c) $Q/D^{5/2} = 10.27$; $H_o/D = 5.03$.
Air being sucked. 0.28D head on high-stage crest.

Figure XV-6.—Trajectory from 1D by D/2 rectang low-stage orifice in downstream endwall and flo bottom of drop inlet and in barrel entrance. B = orifice elevation = 1.25D; series W-560.

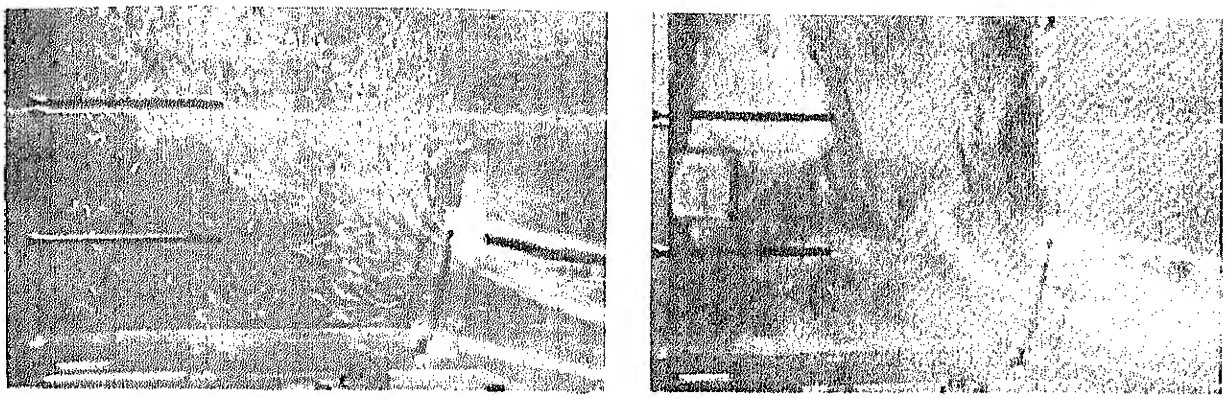
the barrel also primed for the 0D (series W-576), 2D (series W-572) and 5D (series W-575) inlet elevations. Notes for several series comment on the high water surface and turbulence in the drop inlet. This condition exists because the opposing orifices are at the same elevat and the jets impinge on each other. Figure XV shows that flow from the opposing orifices a parently occupies much of the upstream porti of the drop inlet thus forcing the water and a



(a) Jet at upper trajectory.

(b) Jet at depressed trajectory.

Figure XV-7.—Flapping trajectory from 1D by D/2 rectangular low-stage orifice in downstream endwall of dr inlet. B = 3D; orifice elevation = 3.25D; $Q/D^{5/2} = 2.77$; $H_o/D = 1.21$; series W-562.



(a) Orifice flow control at barrel entrance. (b) Air flow through spillway.

Figure XV-8.—Flow conditions in drop inlet with D/2-square low-stage inlets at upstream end of both sidewalls. B = 3D; orifice elevation = 1D; $Q/D^{5/2} = 6.37$; $H_o/D = 5.14$; head on high-stage crest = 0.14D; series W-571.

flow from the high-stage crest into the downstream part of the drop inlet. Obviously, opposing D/2-square orifices located in the sidewalls at the upstream end of the drop inlet produce unsatisfactory flow conditions in the spillway.

Comments.—All tests on the 1D by D/2 rectangular low-stage orifice inlet or variations of it produced less than satisfactory performance. Sidewall orifices seemed to be particularly poor so no further tests were made on low-stage inlets located in the drop inlet sidewalls.

The major difficulty experienced when the rectangular orifices occupied the full width of the two-way drop inlet seemed to be that the jets from the orifices were so wide that there was no opportunity for aeration of their undersurfaces. Therefore, the orifices were narrowed to provide space for the ventilation of the orifice nappes. This proved successful. The test results will be described.

Orifices 3D/4 Square

Orifice in upstream endwall.—When the 3D/4-square low-stage inlet orifice is in the upstream endwall, the notes taken during the tests state that there was good priming action in the barrel for all orifice elevations. The performance ratings for series W-577 through W-582 are good.

The previously reported performances have been for a 3D-long drop inlet. The drop inlet was shortened to 2D and the tests with the 3D/4-square low-stage orifice were repeated. The results are summarized in table XV-1, series W-592 through W-596. The performance was good and close to that reported in the preceding paragraph for the 3D-long drop inlet. The test notes indicate that the flow in the drop inlet was relatively quiet.

Orifice in downstream endwall.—The spillway performance was good when the 3D/4-square low-stage inlet orifice was in the downstream endwall of the drop inlet. This good performance applies to both the 3D-long drop inlet (see table XV-1, series W-583 through W-586) and the 2D-long drop inlet (see table XV-1, series W-597 through W-600).

Orifices in both endwalls.—Low-stage inlet orifices 3D/4 wide by 3D/8 high were placed at the same elevation in both endwalls. The performance was good, the barrel primed and the flow in the drop inlet was relatively quiet for both the 3D-long drop inlet (see table XV-1, series W-587 through W-590) and the 2D-long drop inlet (see table XV-1, series W-602 through W-605).

For series W-591 (3D-long drop inlet) and series W-601 (2D-long drop inlet) the 3D/4-wide by 3D/8-high low-stage inlet orifice crests were 0D above the drop inlet floor for the upstream endwall and 1.25D above the drop inlet floor for the downstream endwall. As indicated in table XV-1, the performances of these inlets were good, and the flow in the drop inlet was relatively quiet.

Comments.—The 3D/4-wide orifices located in the upstream or downstream endwalls of the two-way drop inlet performed satisfactorily. The undersurfaces of the orifice jets were aerated and there was no fluctuation of the jet.

The turbulence caused by the jets was mild. Priming of the barrel was not hindered by the flow from the low-stage orifices.

Orifice Capacity

To compute the orifice capacity, knowing the coefficient of discharge is necessary. The discharge coefficient for the low-stage rectangular orifice was evaluated using the equation developed for computing the discharge from a vertical rectangular orifice under a low head. This equation is

$$Q_o = C_o \frac{2}{3} \sqrt{2g} W_o \left[H_o^{3/2} - (H_o - d_o)^{3/2} \right] \qquad \text{(XV-1)}$$

where

Q_o is the discharge,
C_o is a dimensionless coefficient of discharge,
g is the gravitational acceleration,
W_o is the width of the rectangular orifice,
d_o is the height of the rectangular orifice, and
H_o is the head on the crest (bottom edge) of the orifice.

Any consistent system of units of measurement may be used in equation XV-1.

Orifices 1D Wide by D/2 High

Many of the observed discharge coefficients for the 1D-wide orifice proved to be the same, within the limits of precision of the experiments, as those for the 3D/4-wide orifice. Therefore, although orifices equal in width to the drop inlet width are not recommended because of the resulting poor spillway performance, typical data on their discharge coefficients will be presented.

The data plotted in figure XV-9 are for an orifice 1D wide by D/2 high located at five different elevations in the upstream endwall of a two-way drop inlet. The data for the several orifice elevations terminate at various values of H_o/D because flow occurs over the high-stage crest when the sum of the relative orifice elevation and H_o/D exceeds 6 — the drop inlet height. With the apparatus used for these tests, to separate the flow over the high-stage crest from that through the low-stage orifice is not possible. As a result, computed values of C_o become meaningless when flow occurs over the high-stage crest so they are not shown.

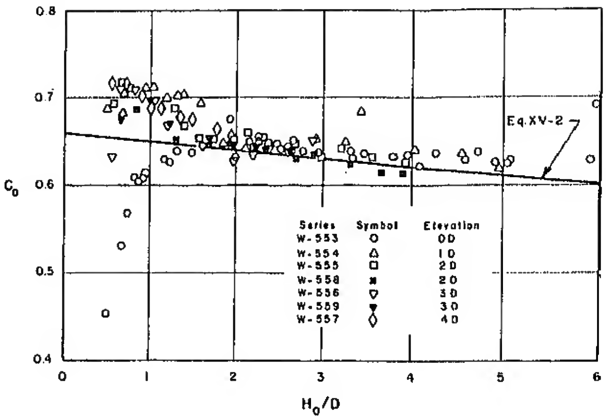


Figure XV-9.—Discharge coefficient for low-stage orifices located in the upstream endwall of a two-stage drop inlet for $B/D = 3$; $W_o/D = 1.0$; $d_o/D = 0.5$.

When the relative orifice elevation is zero (circles plotted in fig. XV-9), the orifice crest is at the elevation of the drop inlet floor, and the jet issuing from the orifice is supported. At low relative heads the discharge coefficient is low and it increases rapidly with the head until $H_o/D \approx 1.5$ to 2.0. Conversely, when the orifice crest is above the drop inlet floor elevation, C_o decreases rapidly with increasing head until $H_o/D \approx 1.5$ to 2.0. At greater relative heads the orifice coefficient decreases gradually with increasing H_o/D for all low-stage orifice elevations. This latter trend is consistent with the trend of published rectangular orifice coefficients.[18]

The line drawn on figure XV-9 has the equation

$$C_o = 0.66 - 0.01\,(H_o/D) \qquad \text{(XV-2)}$$

Although the line is a little low to best fit the data presented in figure XV-9, it was drawn so a single curve would represent the data for all series of tests.

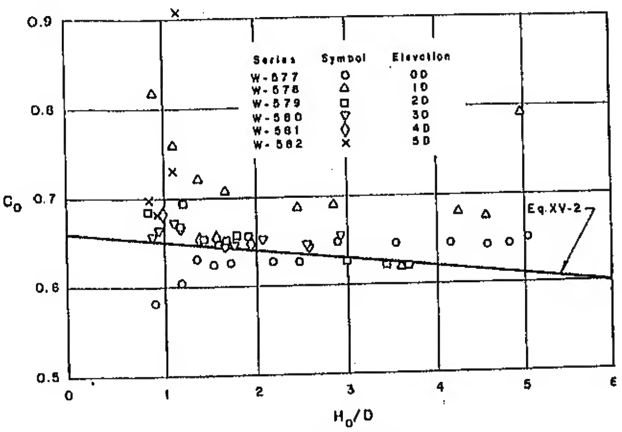
When the 1D-wide by D/2-high orifice was in the downstream endwall, the values of C_o were much the same as when the orifice was in the upstream endwall. A prominent exception is the orifice at an elevation of 1.25D. For this orifice the discharge coefficient jumped from about 0.65 at $H_o/D = 2.6$ to 0.75 at $H_o/D \geqq 2.7$. This

[18] For example: King, H. W. Handbook of hydraulics. Ed. 4, McGraw-Hill Book Company, Inc., New York, Table 25, p. 3-34; Table 26, p. 3-35; Table 27, p. 3-36; and Tables 28 and 29, p. 3-37, 1954.

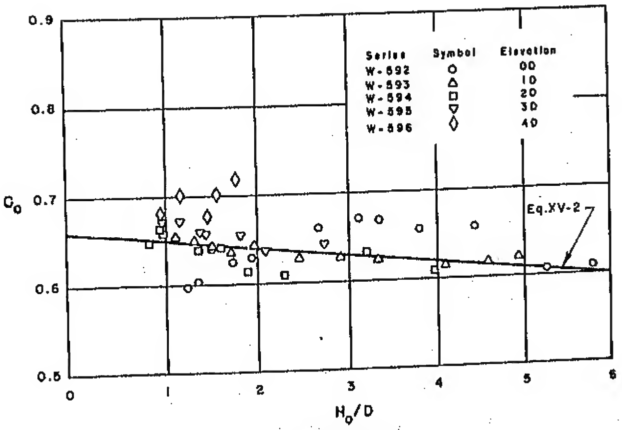
increase was apparently due to suction resulting from slug flow in the barrel. This suction depressed the nappe and also reduced the depth of water in the drop inlet and the orifice submergence.

When the 1D by D/2 orifice was at the upstream end of one sidewall the variation of C_o with H_o/D varied inconsistently with orifice elevation. In general, C_o was well below the curve represented by equation XV-2. Thus, the coefficient data reflect the poor performance reported earlier when the orifice is in one sidewall.

When D/2-square orifices were located in the upstream ends of both sidewalls, equation XV-2 represented the C_o—H_o/D relationship when the relative orifice elevation was 1 or greater. However, when the orifice crest was at the drop inlet floor elevation, C_o was low, varying from 0.49 at $H_o/D = 1.5$ to 0.56 at $H_o/D = 5.75$.

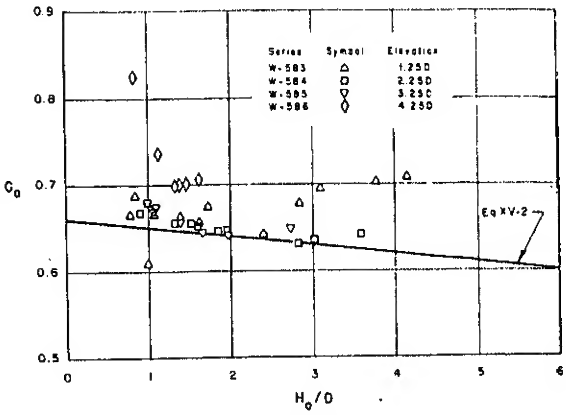


(a) B/D=3

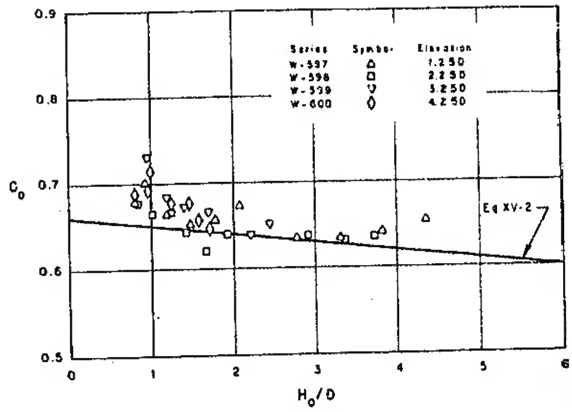


(b) B/D = 2

Figure XV-10.—Discharge coefficient for low-stage orifices located in the upstream endwall of a two-stage drop inlet for $W_o/D = 0.75$; $d_o/D = 0.75$.



(a) B/D=3



(b) B/D=2

Figure XV-11.—Discharge coefficient for low-stage orifices located in the downstream endwall of a two-stage drop inlet for $W_o/D = 0.75$; $d_o/D = 0.75$.

Orifices 3D/4 Square

The data for the recommended 3D/4-wide orifice are plotted in figures XV-10, XV-11 and XV-12 for orifices located in the upstream endwall, the downstream endwall, and both endwalls, respectively, for two-way drop inlets 3D long and 2D long.

In general, the comments made for the 1D-wide orifices apply also to these 3D/4-wide orifices. Equation XV-2 also reasonably represents the data, although there is some scatter in the observed discharge coefficients for which no explanation is obvious.

When the orifice is in the upstream endwall, the data plotted in figure XV-10 show that for

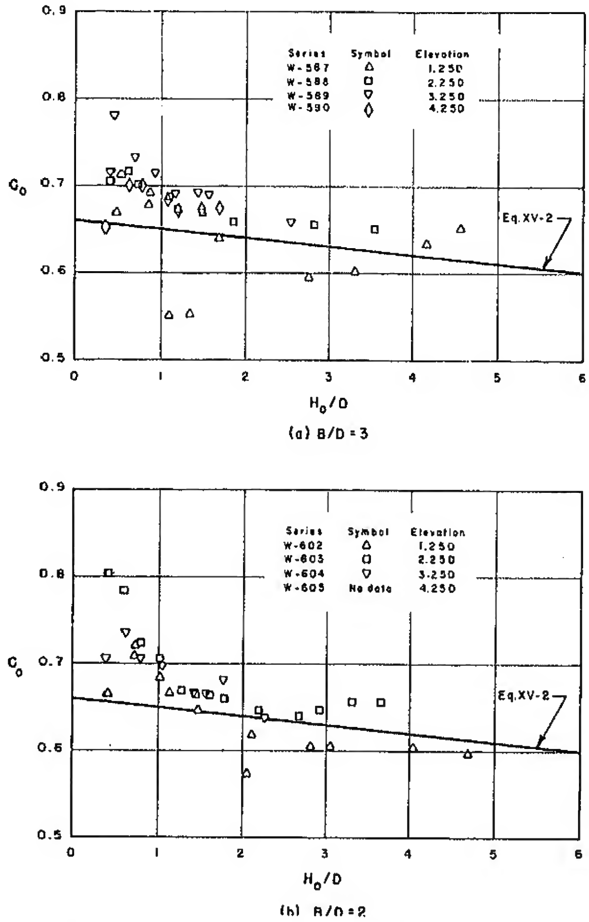


Figure XV-12.—Discharge coefficient for low-stage orifices located in both endwalls of a two-stage drop inlet for $W_o/D = 0.75$; $d_o/D = 0.375$.

H_o/D exceeding about 1.5 equation XV-2 represents C_o to within ±0.03. Exceptions to this are the orifice at the elevation of the drop inlet floor (circles) and the unexplainable values for relative elevations of 1 (erect triangles) when $B/D = 3$ and 4 (diamonds) when $B/D = 2$.

When the orifice is in the downstream endwall, figure XV-11(a) shows major deviation from equation XV-2 occurs for $B/D = 3$ when the relative orifice elevation is 4.25 (diamonds) and for $H_o/D > 2.75$ when the relative orifice elevation is 1.25 (erect triangles). The first deviation cannot be explained. A possible explanation for the second deviation is that at about $H_o/D = 2.6$ slugs begin to form in the upstream end of the barrel. This creates suction which possibly is the reason for the increase in C_o. This same increase in C_o at $H_o/D > 2.6$ was also noted for the 1D-wide orifice located at elevation 1.25D. There is no explanation why there was no similar effect for the $B/D = 2$ drop inlet data plotted in figure XV-11(b).

When the orifice height was halved and orifices were located in both endwalls, some of the data shown in figure XV-12 are erratic. Equation XV-2, however, represents the bulk of the data reasonably well.

Comments

Equation XV-2 can be used to give a reasonably good prediction of the discharge coefficient for the low-stage rectangular orifice. The agreement with the observed data is within about ±0.03 when H_o/D exceeds about 1.5.

Using a constant value of C_o may be sufficiently precise for practical purposes. An appropriate value might be 0.64 because much of the observed data falls within ±0.03 of this value.

The equation for a rectangular orifice under a high head is

$$Q_o = C_o W_o d_o \sqrt{2g(H_o - d_o/2)} \qquad \text{(XV-3)}$$

where $(H_o - d_o/2)$ is the head measured to the center of the orifice. King points out[19] that for a relative head of 2 ($H_o/D = 2$[20]) equation XV-3 gives values of Q_o that are 1 percent greater than those computed using equation XV-1. The corresponding increase in Q_o when $H_o/D = 3$[20] is 0.3 percent. Obviously, the use of the simpler equation—equation XV-3—to compute Q_o for heads exceeding 1.5D is as precise as is warranted by the values of C_o presented herein.

Conclusions

Based on the performance tests the authors

hould not be located in

equal in width to the

[19]See p. 8-9 in reference cited in footnote 18, p. 34.

[20]Russell, G. E. Hydraulics. Ed. 5, Henry Holt and Company, New York; p. 114, 1942, and Daugherty, R. L. Hydraulics. Ed. 4, McGraw-Hill Book Company, Inc., New York, p. 132, 1937, give $H_o/D = 1.5$ and 2.5 respectively.

two-way drop inlet should not be used in the drop inlet endwalls;

3. Low-stage inlets 3D/4 square may be located at any elevation in either the upstream or the downstream two-way drop inlet endwall; and

4. Low-stage inlets 3D/4 wide by 3D/8 high may be located at any elevation in both endwalls of the two-way drop inlet.

Although not based on the tests, apparently the height and width of the low-stage inlet can be varied within reasonable limits as necessary to meet project design criteria.

Based on the tests to determine the capacity of the low-stage vertical rectangular orifice, it is concluded that:

1. The orifice capacity can be computed from the equation

$$Q_o = 0.64 W_o d_o \sqrt{2g(H_o - d_o/2)} \qquad \text{(XV-4)}$$

where

Q_o is the discharge through the orifice,
W_o is the width of the orifice,
d_o is the height of the orifice,
g is the gravitational acceleration,
H_o is the head on the orifice crest (the bottom edge), and
a consistent system of units is used.

2. The discharge computed according to equation XV-4 will represent the actual discharge of orifices similar to those tested to within about ±5 percent.

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